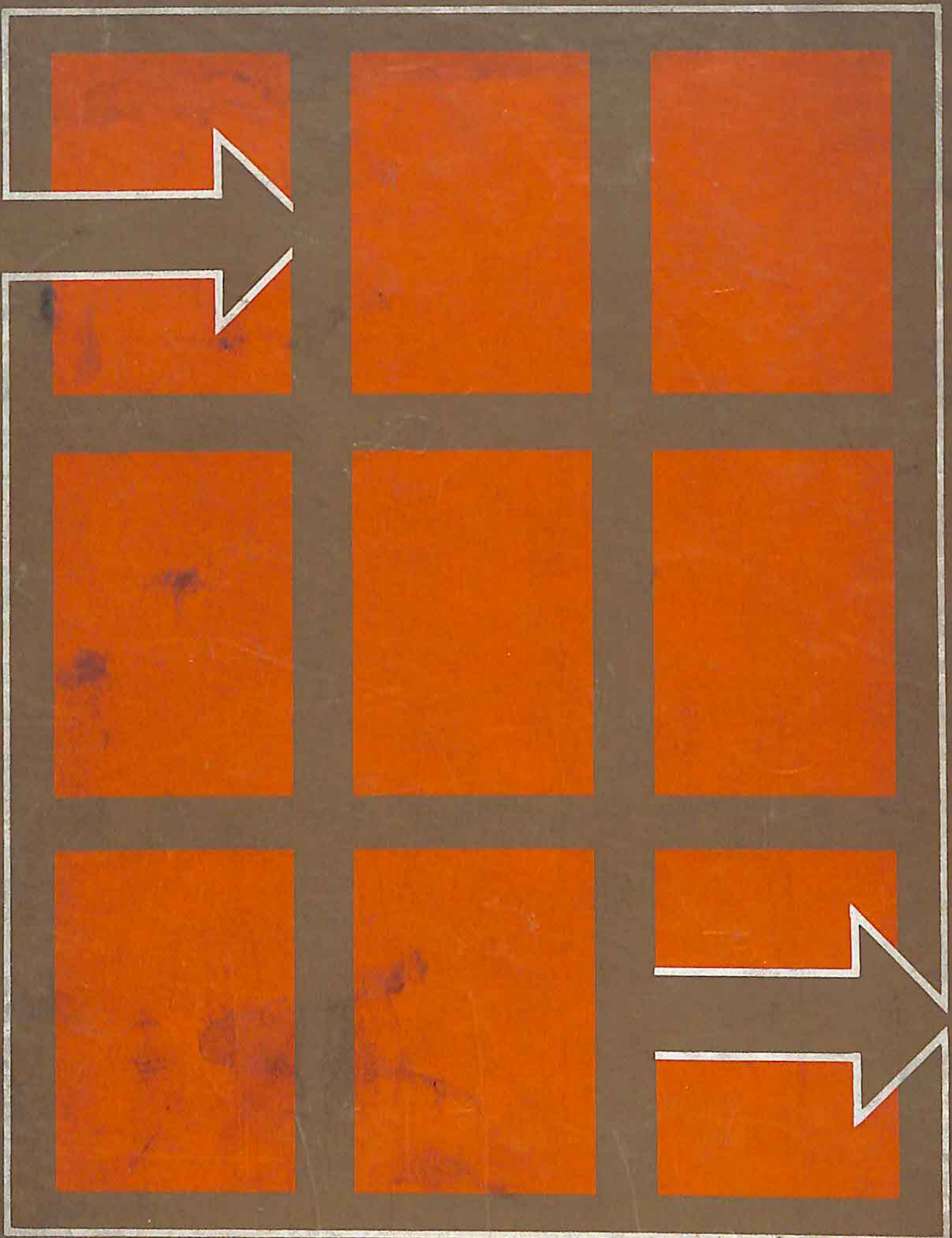
LEARNING & MEMORY



Wayne A. Wickelgren

Learning
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Learning and Memory

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This book is dedicated to my children,

Ingrid Wickelgren

and

Abraham Wickelgren

Using References and Citation Indices

Both original experimental and theoretical articles and review articles and books have been cited in this text. In each case I made a judgment as to whether primary or secondary sources or both would be most useful to the student. If you are interested in pursuing a topic further, you can look up the cited reference in a library. These references will contain still more references. Furthermore, by using *Science Citation Index*, you can search forward in time for related articles published subsequently that cite any article for which you have a reference. Learn how to use *Science Citation Index* as it is a powerful tool. Using it, along with the references in articles to prior related work, you can almost always quickly obtain an enormous quantity of relevant material on any topic, even if you start knowing only one article on that topic. In fact, the major problem is to select from a mass of partially relevant material that which is most relevant to your interests. However, a citation index is an enormous help in selecting material that is relevant to your interests.

Preface

Think about some book you read a while ago, and imagine yourself taking an exam on it today. *How much* would you remember? How much of this material have you later used in some way? Chances are you have remembered and used only a small fraction of all the material presented in the book. *What* do you remember of this material? Probably some of the most basic concepts, a few general principles, and certain specific facts that were particularly interesting or important to you.

I believe there is a message for textbook writers in this common experience concerning the limited quantity and selective quality of human memory. We must emphasize the explanation of concepts and general principles. Specific facts are a means to the end of clear understanding of general principles, not an end in themselves. Furthermore, whenever possible, specifics should be selected which are most likely to be interesting or relevant to the reader's goals and probable life experiences.

Accordingly, this book focuses on explaining concepts and principles, rather than on explaining the results of experiments. A modest number of experiments are explained in some detail to illustrate concepts and principles, but for other experiments only the most relevant facts are presented. Second, there is also extensive use of everyday experiences and practical applications to illustrate important concepts and principles of learning and memory.

Third, I aimed for an integrated presentation of the various topics in learning and memory that is simple, precise, and accurate. I tried to use simple and precise concepts and principles that had great generality in explaining a wide variety of phenomena. I tried to avoid complex theories, vague generalities, narrow theories of particular phenomena, and, of course, inaccurate theories. Simplicity, precision, generality, and accuracy are four criteria for judging a theory in science, and I think these criteria are equally applicable to a textbook.

Fourth, I placed emphasis on learning the precise meaning of the basic concepts used in both theories and experiments in learning and memory. The method I favor for learning this specialized vocabulary is to use the concepts to explain a theoretical principle, fact, or experimental procedure. If a formal definition seems helpful, great; I will use it. But in close proximity to the formal definition will be one or more examples of why knowing this concept (this meaning of a word) is useful.

Fifth, we all know how repetition, particularly spaced repetition, aids learning and memory. Accordingly, I did not assume in a later chapter that the reader necessarily remembered the meanings of specialized terms introduced in earlier chapters. I tried to remind the reader often of the meanings of technical terms when the same terms occurred later in the book. One reason for this is to make each chapter somewhat more self-contained, permitting chapters to be read out of sequence, or aiding the reader who has forgotten the meaning of some important term introduced earlier. Repetition also provides spaced review for the reader who does remember the concept.

Sixth, to assist the reader in organizing the material and to provide spaced review, every chapter begins with a listing of its Objectives and ends with a Summary of the basic concepts and principles discussed in that chapter. The Objectives and Summaries foretell and retell the contents of the chapters in ways that I hope will help the reader to discriminate the forest from the trees, the general concepts and principles from the supporting evidence and illustrative examples. If you find yourself remembering the general principles, but having trouble remembering all the specific examples, that's terrific, don't sweat it. It only proves you are a member of the human race!

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Learning
and
Memory

1 Introduction

OBJECTIVES

1. To introduce some of the basic concepts and principles of learning and memory that focus on practical problems and life experiences rather than more artificial experimental data.
2. To distinguish between *learning* and *performance* and to discuss the roles of motivation and attention.
3. To describe the three basic phases of memory: *acquisition* (learning), *storage* (consolidation and forgetting), and *retrieval* (recall or recognition).
4. To discuss the *encoding of events* using general concepts as distinguished from specific sensory attributes.
5. To define and explain the concepts of *associative* and *nonassociative* memory.
6. To explain the *chunking* capacity of the mind, and how it extends the power of associative memory.
7. To distinguish different types of learning by means of such concepts as: (1) whether the organism is trained to *emit* or *omit* a response, (2) whether the motivation for learning is *appetitive* (to achieve something positive) or *aversive* (to avoid something negative), (3) the number of events on which learning is contingent, (4) how close in time events must be for learning to take place, (5) the role of *preparedness* of an organism for any type of learning, (6) the existence of *critical periods* in which organisms are more highly prepared for a certain type of learning, and (7) the dynamics (rates) of learning and forgetting.

The person I was five years ago no longer exists. Neither does the person you were five years ago. At that time we had different knowledge, goals, and emotions from those we have now. Excluding maturation, illness, and injury, what caused us to change was learning and forgetting.

Do we know more today than we did then? I cannot say, even for myself. No scientist today can answer that question. We can assess knowledge of a particular field by a set of questions drawn from some larger pool, but we cannot assess the total amount of knowledge possessed by any human mind. In many people this total may increase steadily throughout life until they are seventy or eighty. On the other hand, perhaps everyone reaches some maximum quantity of knowledge in their twenties or thirties and merely maintains that level until they are seventy or eighty. It is even possible that the total quantity of knowledge peaks at the time we leave school and declines thereafter. But that *quality* of knowledge continues to be subject to change. In any event, the accumulation of knowledge in our minds changes by both addition and subtraction.

LIMITED CAPACITY

I have often heard the claim that we use only a small fraction of our capacity for learning and memory. Since we cannot measure the total knowledge an individual possesses and since we have no idea of the human mind's maximum capacity, there is no way we can assess the truth of such claims. For whatever it is worth, I hold the opposite point of view: I believe that many people under many conditions are using a rather large part of their learning and memory capacity. However, I believe that much of the knowledge that people learn is far poorer in *quality* than the knowledge they could be learning. We probably learn something every moment of our waking lives, and there may be only moderate variations in *how much* we are learning at various times, but we don't know because there is no evidence regarding variations in the total quantity we learn at different times. A person may have learned very little about a topic during a formal lesson situation, but that does not mean he or she learned very little of anything in that period. That person may have been thinking about and learning more of other things instead of learning the content of the formal lesson. Of course there are different rates of learning for different individuals and for the same individual at different times. However, *what* we learn is almost certainly far more important than *how much* we learn.

Similarly, the evidence suggests that there are only modest differences in rates of forgetting for different individuals when the nature of what was learned is the same. There is little to support the hypothesis that individual differences in intelligence or knowledge are the result of differences in basic memory trace decay rates in the brain. There are differences in *how fast* material is forgotten, but these differences appear to result largely from the way the material was encoded at the time of learning—that is to say, from differences in *what was learned*.

Laboratory studies tend to support common experience: that we forget what we learn unless we continually use—that is, rehearse and relearn—it. Furthermore, the rate of forgetting is very rapid immediately after learning, but it gradually slows down the longer the time since learning. This means that most of us forget most of what we learn the first few days after we learn it.

Part of the reason for this is *interference*. Interference is subsequent learning that uses some of the same concepts used in the earlier learning in such a way that it interferes with our ability to remember the previously learned material. There is a story (presumably apocryphal) that illustrates how interference works: A professor of ichthyology became a college dean. After his appointment he claimed that every time he learned a student's name he forgot a fish!

We can counteract this forgetting for any given knowledge by periodic review, but while we review some material we are losing other material, and we are not using the time to acquire new knowledge. We must accept that the human capacity for learning and memory is substantial but not unlimited—indeed, we may well be operating close to that capacity in quantity, though not in quality, of knowledge.

The hypothesis that human beings operate fairly close to their quantitative learning and memory limits has a number of important consequences. For example, in education emphasis should be on the quality rather than on the amount of knowledge that students are required to learn. What is high-quality knowledge? I would say it is knowledge that we can *use* to achieve some important goal. Such knowledge includes general concepts and principles that give us insight into and understanding of facts and experiences. It is also knowledge that satisfies our curiosity and integrates separate aspects of human experience.

The curricula of elementary and secondary schools teach much that is generally useful, but a wider acceptance of the idea that learning and memory capacities are limited might produce important change in some aspects of public education. For example, it is of far less general value to know the superficial physical characteristics of various plants and animals than to know about nutrition, disease, first aid, the anatomy and physiology of the human body, and the general principles of living systems. It is also debatable whether a child ought to be taught a foreign language. The more a child in an intellectually rich environment learns about one thing, the less he or she learns about other things. Directing part of a child's time to the learning of a foreign language might result in less conceptual growth in other areas. There are substantial social, personal, and intellectual values to foreign language learning, but its inclusion in elementary and preschool curricula is certainly open to question.

With so much you might do to improve the quality of your knowledge, there is little reason to be discouraged by the possibility that you cannot greatly increase the quantity of your knowledge beyond that which you possess today. There is something to be gained in human happiness by the explicit recognition that our memory capacity is limited, if we adjust expectations for our own performance and the performances of others accordingly.

The concern some people have about their "bad memories" is misguided. Memory capacity varies for different individuals. The person who remembers people's names or some other class of things expecially well is not necessarily a person with higher general memory capacity than the individual who has trouble remembering these things. People who know much about some topics have spent much time learning about them, and have therefore spent less time learning about other topics and will generally be less informed about them than you are. There is a trade-off between studying and doing. Most of us wish to use our knowledge to accomplish something. Some people who know more than others have accomplished less as a direct result of their learning.

Recognizing that memory capacity is limited can make one more sensitive to and sympathetic with the memory limitations of others. It is unreasonable to tell a coworker or friend, in a five-minute period ten different things you want that person to do and expect him or her to remember it all without mistakes. When you have to give someone lots of instructions, a great deal of it should be in writing. One source of friction in personal relations and of inefficiency in job performance could be eliminated if we remembered that the capacity for learning and memory is limited.

LEARNING AND PERFORMANCE

My seven-year-old daughter Ingrid learned how to make her bed a few months ago. Abe, her five-year-old brother, has not yet learned to to make his bed. On what basis do I make such statements regarding what my children have or have not learned? I make them by observing their performance. However, there are important complications to inferences about learning and memory on the basis of performance.

The most important complication is motivation. Unless an organism is motivated to perform a learned task, we cannot infer the absence of learning from the absence of task performance. If Ingrid does not make her bed one day, I do not conclude that she has forgotten how to do it; I conclude rather, that, for one reason or another, she did not adopt that as a goal today. Furthermore, since she is an independent person, and since I have never delivered any punishments contingent upon failure to make her bed, my pointing out to her that she has not made her bed will not necessarily lead her to do it. Since she sometimes wants to make her bed and does it, her failure to perform this task on other occasions is most reasonably interpreted as unwillingness to adopt the goal rather than as any deficiency of learning and memory.

Abraham has never yet made his bed to any minimally satisfactory extent, although he has made a couple of attempts at it. I think he had sufficient motivation to perform the task when he did try, so his failure represents lack of knowledge and skill. However, it is not safe to conclude that he cannot learn to make his bed. At his age he undoubtedly can, provided he is induced to adopt this as an important enough goal to keep working at. What a child (or any other organism) can or cannot learn is as much a matter of motivation as it is of cognitive (learning) capacity.

Perhaps the most striking illustration for me of the importance of motivation for performance came in the area of toilet training. When Abe was a little over two years of age, he wanted very much to go to preschool with Ingrid. I told him he could go when he became toilet trained. Much to my surprise he adopted this subgoal with a dedication far beyond his years. I also promised him some very attractive toy should he become toilet trained. Thereupon, he began suggesting a host of other toys that he should receive if he became toilet trained. He talked continually about all the things he was going to get when he became trained, and it seemed to have a profound effect upon him, because he was completely trained in less than a month and remained trained for almost a year. Unfortunately, not wetting his pants ceased to be important to him, and he so regressed that for several years he did not achieve the same high reliability of performance that he had achieved as a two-year-old.

Performance is also affected by attention. If an organism is not attending to the relevant cues, one cannot infer the absence of learning from performance failure. My children have been taught that they are supposed to close outside doors after they go through them. They can even tell you why: to keep the cold air out in the winter and to keep the bugs out in the summer. Their frequent failure to perform this task might be attributed to lack of motivation, but the task is very simple and when I draw their attention to the need to close the door, they are generally quite willing to do it. Likely as not, they are simply not attending to the relevant cues; they don't even notice that they have left the door open. If when I announce to them in a loud voice that dinner is ready and they do not come, the reason is probably not lack of appetite or failure to understand my words. Rather, they are so engrossed in what they are doing that they simply do not attend to what I am saying.

Motivation and attention are the two processes that interact with learning to determine performance. We can infer the presence or absence of learning and memory on the basis of performance only when we are satisfied that the organism is motivated to perform the task and is attending to the relevant stimuli.

Motivation is typically controlled in animal behaviors studies by manipulating primary drives such as hunger and thirst through food or water deprivation. If an animal that we know is very hungry fails to take the correct turn in a T maze to receive food, it is reasonably safe to infer that failure to perform the correct response was not based on lack of motivation. Controlling the stimuli that animals choose to attend to in a learning task is considerably more complicated, and performance in many animal learning situations is as much a matter of teaching them to attend to relevant stimuli as it is of getting them to associate these stimuli with each other or with responses.

Adult humans understand language and have generally been socialized to be cooperative with psychology experimenters, so controlling their attention and motivation in an experimental situation is rarely a problem. Hence, learning and memory is much more easily inferred from the performances of adult humans than from those of either animals or children. It is more difficult to study cognitive and learning capacities in children than in either adults or animals, because the attentional and motivational processes of children are more difficult to control by instructional means than those of adults, and because one cannot do the motivational and physiological manipulations and measurements that one can with animals. In view of this, it is not surprising that theories of learning and cognition are more precise for adult human beings and animals than for children.

MEMORY AND MEMORY TRACES

The term *memory* has many different uses. In common parlance memory usually refers to a conscious recollection of some prior experience, but psychologists use the term more broadly, to refer to a wide variety of changes in the nervous system that result from experience and that can affect behavior. Conscious awareness is not considered a critical defining attribute of a memory.

There are many other kinds of records besides psychological memory that are often referred to as memories. There are *physical memories,* such as those produced on magnetic recording tape, a record disc, a calculator or computer memory storage cell, a computer card, a table of numbers, a page from a book, a knife scar on a tree, a scar or scab or bruise resulting from bodily injury, and so on. There are more uniquely *biological memories,* such as changes in motivation that result from deprivation or stimulation, changes in the muscles or circulatory system that result from exercise, and immunological memories that result from exposure to germs and nonreproductive allergens.

This book focuses on psychological memory, but other kinds of memory will sometimes be cited to provide clear examples of basic concepts and to broaden perspective. Furthermore, it is now clearly established that there are several different modalities of psychological memory in the human mind, such as visual-spatial versus verbal memory. It is not known how many different types of memory exist in humans and lower animals, and I think it a mistake to prescribe tight definition of what to include or exclude in psychological memory. We shall consider a wide variety of learning and memory phenomena, and consider in each case the general principles that best explain the phenomenon in question.

What changes inside us when we learn things? Something must change if there is to be a systematic change in performance. The term *memory trace* refers to the change that occurs as a result of learning. The terms *engram* and *memory state* mean the same thing as *trace*. The terms *association* and *habit* are also sometimes used to refer to the change established by learning, but these terms make some assumptions concerning the nature of the memory trace and so are not theoretically neutral. Use of the term *trace* assumes nothing more than that learning produces some change in an organism. In particular, it should not be taken to mean that memory is like a mark or groove that becomes deeper in learning and fades away in forgetting. Nor should it be assumed that a particular memory trace is located in a specific part of the brain. One of the fundamental issues in the physiological basis of memory concerns whether a specific memory trace is produced by a change in a specific part of the nervous system or whether it is the result of changes that are widely dispersed throughout the nervous system.

ACQUISITION, STORAGE, AND RETRIEVAL

One of the most important distinctions in the analysis of learning and memory is between the three principal phases of the memory process: acquisition, storage, and retrieval. A memory must go through all three phases to have any psychological function. First, a trace must be acquired (learned) as a result of some experience. In most treatments of learning the terms *acquisition* and *learning* mean the same thing. They will be used interchangeably throughout this book. Acquisition is discussed in Chapter 13.

The *retention interval* is the period between the end of learning and the time a memory trace is retrieved or used in some way. The *storage* phase concerns the processes that affect the memory trace during the retention interval. Three different types of processes may affect memory traces in storage: *rehearsal, consolidation,* and *forgetting*. We all know that memory traces can be consciously *rehearsed* in the retention interval. Such rehearsal is both a storage maintenance process and an acquisition process. Memory traces may also be unconsciously *consolidated,* though the existence and nature of such consolidation is the subject of some dispute. Finally, memory traces are *forgotten* during the storage period because of a loss of trace strength or because of a decreased accessibility. Such losses during storage in memory strength or accessibility may be caused by *decay*, as a result of the passage of time, or by *interference* from prior or subsequent learning, or both. We shall discuss these hypotheses in Chapter 14.

A memory trace must be used in some way to affect perception, thinking, or behavior, and the process of using it is typically called *retrieval*. From a psychological standpoint, we cannot know that a memory exists unless it can be retrieved in some way that affects behavior. Whenever a previous experience affects some characteristic such as the probability, amplitude, or time of occurrence (latency) of some response in a situation, we infer that a memory trace for that experience must have been retrieved in some way to influence behavior. This is a very general interpretation of retrieval. It is not satisfactory to think of retrieval as a mental analogue of finding a memory trace somewhere and bringing it over to some other place to be used. Some theories assume that retrieval is a *search* process, but *direct-access* theories argue that retrieval involves no search at all.

Recall and Recognition

Most studies divide retrieval into two basic categories: *recall* and *recognition*. The distinction between recall and recognition is essentially the same as the distinction between wh-questions (who, what, when, where, which, and how) and yes-no questions. The question "Who was the first president of the United States?" tests recall, whereas the question, "Was John Kennedy the first president of the United States?" tests yes-no recognition. Somewhat more common than these yes-no (true-false) recognition memory questions are *multiple-choice* recognition memory questions of the form "Who was the first president of the United States: John Adams, George Washington, Abraham Lincoln, or John Kennedy?" Although this multiple-choice recognition question is grammatically a wh-question, psychologists put it in the class of recognition memory rather than recall, because the alternative answers are explicity presented and the correct answer need only be recognized.

Memory for Names

The distinctions between acquisition, storage, and retrieval seem obvious once they are pointed out, yet in common parlance the distinctions are often ignored in ways that produce confusion. For example, consider the all-too-human tendency to "forget" someone's name. Most people say that they have a poor "memory" for names, and many feel that this says something so negative about their general memory capacity that they will rush out and buy a book that promises to give them a "steel trap" memory for names and other relatively meaningless material that is difficult to remember. If it is really important to you to improve your memory for names, then you should first diagnose the nature of the problem. For many people the terms *forget* and *memory* refer primarily to the storage phase, but in remembering names the most common source of trouble is in the acquisition phase. Most people do not remember names because they do not pay much attention when they first learn them.

As proponents of memory systems have pointed out, different ways of encoding the material at the time of acquisition have different consequences for the rate of forgetting in storage. If you attempt to learn a name merely by repeating it over and over, you will probably only remember it for a few tens of seconds after finishing your rehearsal. Such phonetic (auditory and/or articulatory) encoding of a name as a sequence of sounds is subject to a great deal of interference from all of the sounds that you hear and say during the time that elapses between when you first rehearse the name and the time that you are required to recall or recognize it. By contrast, you might think of a more meaningful (semantic) technique for encoding the relationship between some characteristic of the person and the name, such as noting that Fred has red hair and that red is a portion of the name Fred. Such encoding improves retention of a name because the association will be less subject to interference. Changing the nature of the encoding may have a profound effect on the rate of forgetting during the storage phase, but the quality and quantity of the encoding are both parts of the acquisition phase. According to the present evidence, differences in memory are primarily the results of differences in the quality and quantity of initial acquisition.

Sometimes we can't remember names because of a difficulty in retrieval. For example, the cues at the time of retrieval may be very different from those at the time of acquisition, such as when we see people in very different contexts from those in which we originally met them. Another factor that appears to affect memory for names is an excessively high level of anxiety at the time of retrieval. If suddenly you have to introduce two people, the rush of anxiety you experience concerning your ability to remember their names may interfere with retrieval.

ENCODING OF EVENTS BY CONCEPTS

An *event* in your life is anything you experienced in some brief period. We cannot now say much about how long the time period is for a psychological event, nor even whether psychological events are best considered discrete or continuously merging into each other. Nevertheless, it is useful to consider life to be a succession of events, where an event is the totality of our experiences during some (undefined) period.

To perceive an event, a human being must represent the event in some manner in the nervous system. This representation is often referred to as the *encoding* of the event. Perceptual encoding occurs almost simultaneously at several different levels of the nervous system—from the peripheral sensory receptors to the highest levels of conceptual thought. A kiss is encoded at the periphery of the nervous system by activation of a set of tactual, visual, and perhaps auditory and olfactory sensory receptors, but it may also be encoded at a higher conceptual level as "Cindy likes me," "Cindy loves me," "Cindy is leaving for work," etc. Perceptual encoding of a specific stimulus at lower sensory levels is invariant. At higher conceptual levels it is much more variable, because it depends both upon context and the memories of the perceiver.

We can distinguish between perceptual encoding and encoding into memory, because memory traces established at the peripheral sensory levels decay or are interfered with much more rapidly than traces established at the central conceptual levels. A few seconds after an event occurs, we have a fairly precise sensory memory of its physical attributes, but later we ususally retain only the higher-level, semantic (meaningful or conceptual) encoding of the event. Long-term retention of images also occurs, but such long-term image memory is generally rather abstract—not at all like a sensory afterimage, for example.

Under normal conditions encoding into memory apparently occurs simultaneously with the encoding that mediates perception, behavior, and thought. Indeed, memory traces may well be established in precisely the same places in the brain that are responsible for perception, performance, and cognition. However, as we said before, conceptual traces last much longer than peripheral sensory traces.

Encoding in long-term memory is thus both *abstract* (selective) and *categorical* rather than a complete and detailed record of all the sensory attributes of events. One reason that long-term memory is abstract may be selective attention at the time of perception: we simply do not consciously attend to most of the stimuli that impinge upon our receptors. However, much of the abstract categorical nature of long-term memory is because of the nature of the concepts used to encode events at the semantic level.

What do you remember about your evening meal yesterday? You probably remember what you ate, but not its arrangement on your plate, though you clearly attended to the food arrangement at the time of eating. (People do not blindly jab their fork at the plate and eat whatever they pick up.) You can probably conjure up some memory for the taste of the food, but, unless last night's dinner provided an unusual taste sensation, your memory of the food is largely categorical. You may remember that you had fried chicken, mashed potatoes, and peas, but your memory is in terms of general concepts, like fried chicken, mashed potatoes, and peas, and it is the associations from the concept "last night's dinner" to each of these general food concepts that you can now recall.

ASSOCIATIVE AND NONASSOCIATIVE MEMORY

Memory traces can be classified as associative and nonassociative. The idea of associative memory has been around since Aristole. In this section we shall define associative and nonassociative memory and provide several examples of each type.

Nonassociative memories are records of events that are encoded and stored in locations (cells, registers, boxes, and the like) in the order that they occur. There are one-dimensional nonassociative memories, for example the columns of an IBM card, the successive sections of magnetic recording tape, or the successive character positions in the lines of print in a book. There are also two-dimensional nonassociative memories, as in a table, chart, or picture.

Associative memories are records of events that are encoded and stored by networks of nodes (internal representatives of events) that are connected with each other by means of associations. These associations may vary in strength and perhaps in other ways as well. Virtually every theory of associative memory has assumed that associative strengths are increased by the activation of two nodes close together in time. As we shall see, however, strength of association between two nodes can represent more than simple succession of events.

Associative memories are found almost exclusively in the nervous systems of living organisms, and it is very hard to find other examples. Imagine that you are studying the interactions of four people in a small group. The individuals are supposed to interact only in pairs, and you are recording how often various pairs interact. You could use a nonassociative memory for this interaction pattern, by recording all the events as they occurred in successive lines of your notebook by means of a conceptual notation such as *CD, AC* (meaning *C* and *D* interacted, then *A* and *C* interacted), and so on. Or you could use an associative memory such as the one shown in Figure 1-1. In this associative memory, you represent each individual only once. You record the frequency of interaction for each pair by adding to the strength of association between each node (represented by the picket-fence number on the line between each pair of nodes).

If all you ever want to know about this small group experiment is how often each pair of individuals interacted, this associative memory is very efficient. In acquisition (recording) you just add another mark on the appropriate line every time an interaction occurs. Storage is very economical, requiring only a part of one sheet of paper. In retrieval, it is easy to see how many times each pair interacted (that *A* interacted the most, etc.). But, if you want to know things that depend upon the exact sequence of events, such as whether *D*'s interactions with *C* tended to precede, follow, or be unrelated to *C*'s interactions with *A*, the associative memory in Figure 1-1 will not help. The basic purpose of an associative memory is to increase the

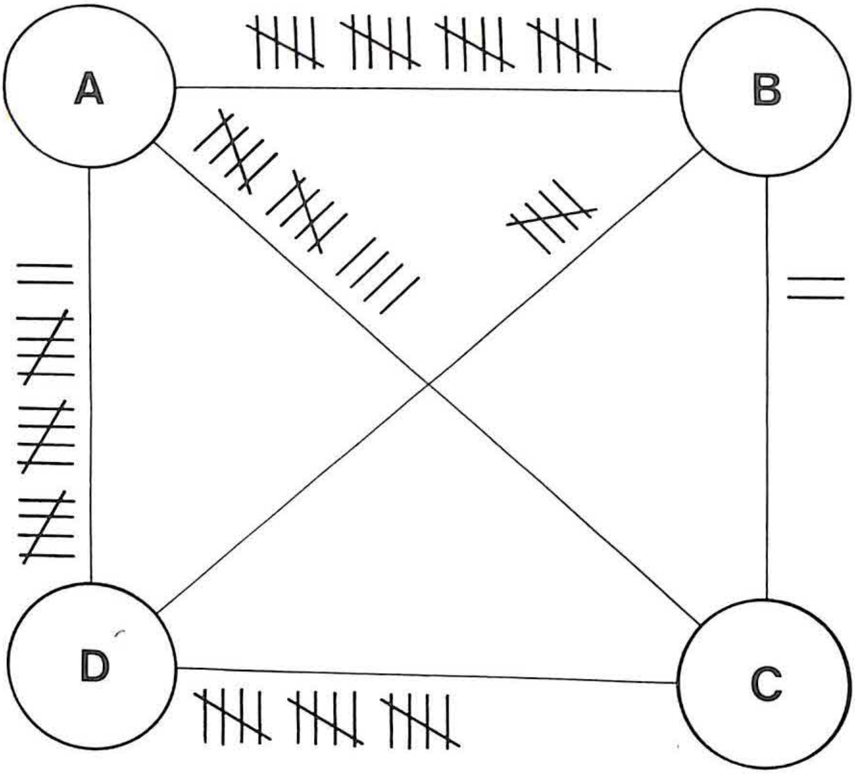

Figure 1-1. An associative memory for recording the number of times each pair of individuals (*A*, *B*, *C*, and *D*) interacted in a small-group experiment. The four nodes represent the four individuals, and the picket-fence count on the lines (association) between each pair is the number of times those two individuals interacted.

efficiency of acquisition, storage, and particularly retrieval. In doing so it ignores many aspects of the temporal sequence of events.

The basic purpose of many nonassociative memories is to record the exact temporal sequence of events; but one must do much processing of such memories at the time of retrieval to answer any question, such as how often *A* and *B* interacted or whether *B* and *C* interacted at all. To answer a question, such as how often *A* and *B* interacted, with a nonassociative memory, one must successively (serially) *search* for the *AB* pair representatives, through all the memory storage locations. With the associative memory shown in Figure 1-1, we have what is called *direct access* to how often *A* and *B* interacted. We just have to look at the number of marks on the line between *A* and *B*.

Almost all of the external memories used by humans, such as books, articles, lecture notes, tape recordings, and the like, are nonassociative memories. The integration of all the separate associations that go with each concept discussed in a book is not done in the book but in the mind of the reader. A book would be an associative memory if every concept that was used in it was printed only once, and connections (associations) were made in some way between these words so as to represent all of the sentences of the book.

The index of a book is actually the only associative memory component of a book. The index lists many (but for from all) of the concepts in the book and records the page numbers where these concepts are related to other concepts. However, the memory for the exact relations between concepts is by means of the sentences printed on a page. Such sentences are stored in a purely nonassociative manner by a sequence of letter patterns impressed on an ordered set of locations on the page.

Event Representation

In a nonassociative memory the representation of an event is defined to be a particular set of patterns impressed upon any location in memory. The patterns represent the concepts used to encode the event. It is rather like a computer card, where each letter of the alphabet is represented by two holes punched in any column of the card. For example, *T* is a punch in the 0 row and a punch in the 3 row. Just as the same *T* pattern can be punched into several different columns of a computer card, so there can be many identical pattern representatives encoded in different locations in the memory (many *tokens* of the same *type*), as when the "same" event occurs at different times. If the same word occurs repeatedly in a tape recorder memory, each occurrence will impose (approximately) the same pattern on physically different sections of tape. If human memory were like a tape recording, one might imagine the pattern representation of an event being impressed on the "current" location and the patterns for the next event being impressed on the "next" location, etc. As we shall see, human conceptual memory is nothing like a tape recording.

In an associative memory, an event is represented by a particular node (element) or set of nodes. The nodes represent the concepts used to encode the event. The most important property of an associative memory is that when the "same" event occurs at a later time, precisely the same node or node set is activated. This contrasts sharply with a nonassociative memory in which multiple token representations are impressed in different locations when the same event occurs at different times. An associative memory thus achieves an important economy in the representation of events: that time itself is irrelevant to the internal representation of an event. Of course, two events are never exactly the same, so "same" events are those that are classified as equivalent by an organism.

This property of *specific-element representation* in an associative memory is almost precisely the same concept as the famous principle of specific nerve energies formulated by physiologist Johannes Müller in the early 1800s.[1] According to this principle, it is not the *pattern* of firing of neurons that represents particular sensory or motor events, but the *specific nerves* that are fired. The truth of this principle is now well established for the peripheral nervous system. Any stimulation of the auditory nerve will produce the sensation of sound, and no stimulation of the auditory nerve will produce the sensation of seeing or feeling, nor will it produce a grasp or a kick (except indirectly, after processing by the central nervous system).

Neurophysiologists have recently extended the evidence for the specific element theory of neural encoding to more central levels of the nervous system. As a result of the pioneering work of Hubel and Wiesel, we know that single neurons in the visual cortex respond vigorously to simple patterns of visual stimulation.[2] These patterns include lines (edges and slits) and angles presented at specific orientations over a range of locations in the visual field. Some simple cortical neurons appear to encode a simple conjunction of lower-level features, namely, light or dark spots in a straight line. Other, more complex cortical neurons encode a disjunction of conjunctions of specific features. That is to say, these complex line detectors require input from a set of lower-level spot detectors that lie on a straight line, but any linear set of spots oriented at the same angle over a range of possible locations will activate the neuron. Such a complex visual line concept computes a logical function of the form: (A_1 and A_2 and . . . and A_n), (B_1 and B_2 and . . . and B_n), to (Z_1 and Z_2 and . . . and Z_n), where the As are the attributes (features) in one conjunction, the Bs the attributes in another conjunction, etc. In this way, higher-level neurons stand for logically complex combinations of lower-level neurons, but in a way that is still based on the principle of specific-neuron representation formulated by Müller over a century and a half ago. The same specificity holds for motor systems. Activation in some central motor units is strictly correlated with the performance of certain motor movements, even specific complex sequences of movements such as walking, eating, spitting, incubation of eggs, attacking, and the like.[3]

Motivation also appears to use specific-element representation.[4] Activation of specific brain centers produces hunger, as evidenced by eating and food-seeking behavior; thirst, as evidenced by drinking and performance of learned responses to get water; sleep as evidenced by ZZZ. Stimulation of the satiation center turns off hunger. Some years ago Olds and Milner discovered "pleasure centers" in the brains of rats. When these centers were stimulated electrically, the rats experienced such great pleasure that they learned to perform responses for the reward of electrical stimulation of these pleasure centers.[5]

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[1] See R.J. Herrnstein and E.G. Boring (eds.), *A Source Book in the History of Psychology*. Cambridge: Harvard University Press, 1968, pp. 26-33.

[2] D.H. Hubel and T.N. Wiesel, "Receptive Fields, Binocular Interaction and Functional Architecutre in the Cat's Visual Cortex." *Journal of Physiology*, 1966 (160), 106-54. D.H. Hubel, "The Visual Cortex of the Brain." *Scientific American*, Nov. 1963 (209), 54-62.

[3] P.M. Milner, *Physiological Psychology*. New York: Holt, Rinehart and Winston, 1964, pp. 82-99, especially p. 96.

[4] *Ibid.*, pp. 297-377. J.A. Deutsch and D. Deutsch, *Physiological Psychology*. Homewood, Ill.: Dorsey Press, 1973, pp. 406-11, pp. 587-640.

Retrieval: Search versus Direct Access

In computer terminology the representation of events in a nonassociative memory is said to be *location addressable,* because one can go directly to a particular location. One cannot go directly to a particular event representation. To locate a particular event representation in order to answer questions such as whether the event ever occurred before or what the next event was, one must serially (successively) *search* through all the locations in memory. Searching for such a representation in a large location-addressable memory can be very time consuming. Digital computers typically use nonassociative, location-addressable memories, though associative memories can also be programmed to some extent.

In an associative memory, presentation of an event is assumed to *directly access* (activate) its internal representation (node). When the same event occurs again, the same nodes are activated (directly accessed). It is not necessary to do any serial searching of locations for the internal representation of that event, as one must with a location-addressable memory. In the brain, a neuron that represents a line segment of a certain length and angular orientation located at a specific place in the visual field will be directly activated by the appropriate stimulus. The connections from the appropriate combination of lower-level visual spot nodes to this line segment node are already wired into the nervous system.

In computer terminology, an associative memory is often referred to as *content addressable,* because one can employ a program in conjunction with the same location-addressable hardware to permit direct access to a location with a particular content. Even with the high search-speeds characteristic of modern digital computers, it is clear that to apply computers to information storage and retrieval on any large scale, it is essential to develop associative memory systems.

Comparing human and computer memory systems provides an interesting perspective. The terms of such comparisons will change, of course, as we continue to improve computer hardware and software (programming). The advantages of the human nervous system over present computers are the large number of elements (about 10^{10} neurons) and connections (about 10^4 per neuron in the cortex) and a substantial degree of parallel (simultaneous) information processing. Computer systems have a smaller number of elements, a very limited degree of connectivity between the elements, and almost exclusive reliance on serial (successive, sequential) processing, but they have a vastly higher speed of operation than the human nervous system.

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[5] J. Olds and P. Milner, "Positive Reinforcement Produced by Electrical Stimulation of Septal Area and Other Regions of Rat Brain." *Journal of Comparative and Physiological Psychology,* 1954 (47), 419-27.

Hybrid Memories

We are not likely to see rapid development of computer memories that are fully associative in the way that the human nervous system is. What does appear to be feasible is a sort of hybrid, a combination of associative and nonassociative memories in the following form. Information (say in a document) will still be stored in some nonassociative manner (probably graphic storage similar to a photograph or microfilm), but each document will be indexed by a large number of terms, and any of various combinations of indexing terms will provide relatively direct access to the document through a sorting tree that is a functional analogue of associative memory. But because the document will not be fully indexed by the associative memory, there will always be some types of search that cannot be carried on by means of the direct-access, associative component of this hybrid memory system, that will have to be done by means of serial search of the various locations.

Some memory psychologists talk as if human conceptual memory has this sort of hybrid character when they refer to memory as analogous to a file cabinet, or when they make a distinction between *available* information and *accessible* information. The indexing cues yield the directly-accessible information, but other information is potentially available by virtue of having been stored somewhere in the system. However, a considerable serial search of terminal locations of the sorting tree might be required in order to retrieve such available, but not accessible, information.

For example, let's assume that you want to buy a house and have gone to a real estate agent who has stored the photographs, floor plans, and descriptions of some 50,000 homes in such a hybrid computer memory. Naturally you can't take the time to scan the descriptions of these 50,000 homes to find the one best suited to your needs. Fortunately, each of the homes is classified according to various attributes (indexing or retrieval cues): geographical region, amount of land, number of bedrooms, number of rooms, price, presence or absence of fireplace, swimming pool, etc. By choosing the proper retrieval cues you can have direct access to exactly the set of homes that meets your specifications: three bedrooms, $40,000–$50,000 price range, fireplace, in any of three geographical regions. However, not all the attributes that are important to you (wooded lot as opposed to a lawn, acoustic separation of the bedrooms from the rest of the house, etc.) have been used to index the home descriptions. To determine which house meets *all* your specifications, you have to look at the entire set of homes that the computer said met your other specifications.

Conceptual Memory is Associative

We do not know whether human memory is fully or only partly associative, but most evidence supports the hypothesis that it is at least partly associative, and not at all like a tape recording. If you ask yourself, "What did I do on May 3, 1971?" or "What do I know about science?" very little of what you know comes to mind, but you do know the answers to an enormous number of more specific questions. Human conceptual (semantic) memory involves *associating* particular concepts, events, facts, and principles with each other, but to retrieve information you must give your memory fairly specific cues. You cannot look through it as if it were a movie, with everything stored in chronological order, or a filing cabinet, with all the information about any given topic stored in a specific folder. Your memory makes an enormous number of very specific cross-classifications in in a rich network of associations. The evidence supporting the associative nature of human conceptual memory is discussed in detail in Chapter 9.

Examples of Nonassociative Memory

Most human memory is associative, but some kinds are nonassociative. For example, the visual sensation in your eye persists for a time following termination of the visual stimulus. This is called *persistence of vision,* and it is what helps to make a movie appear continuous when in reality it is a rapidly-presented series of discrete pictures. Persistence of vision typically lasts for only a small fraction of a second, but when a very bright stimulus is presented against a dark background the visual memory can last for several seconds. Regardless of how long it lasts, persistence of vision is a nonassociative memory, because a pattern of stimulation is impressed on a location, but no associations are formed between the same patterns or between related patterns in different locations.

Another example of nonassociative memory is visual adaptation. When you enter a dark movie theater, you may experience some difficulty in seeing, depending on how dark it is and how bright it was outside, but after some time in the dark you can see much more clearly. This gradual enhancement of your ability to see under dim illumination is called *dark adaptation.* If it is still daylight, when you leave the theater, you may be temporarily blinded by glare. Your subsequent adaptation to more brightly illuminated conditions is known as *light adaptation.*

Light and dark adaptation are not usually considered examples of learning, but they clearly fall within our earlier definition of learning as "some change in the functioning of the nervous system as a result of experience."

In this case the changes are relatively short-term, on the order of tens of seconds to minutes, and are surely restricted to the visual sensory system; but inasmuch as other forms of strictly sensory changes such as persistence of vision are now considered within the broad scope of learning and memory, there seems no reason to exclude adaptation from this category. The broad view provides useful perspective on the differentiating properties of other forms of learning, and therefore is extremely useful in increasing our understanding of all forms of learning and memory.

Persistence of vision and sensory adaptation are nonassociative memories because they are produced by changes in the state of activation or sensitivity to activation of some elements (nodes) in the system. In this case the changes are probably largely in the receptor elements (rods and cones) or neurons in the eye. It is primarily the nodes themselves whose characteristics have changed, rather than the connections (associations) between nodes. A more detailed discussion of sensory memory is presented in Chapter 8, together with the evidence for classifying persistence of vision as a nonassociative memory.

CHUNKING AND VERTICAL ASSOCIATION

Associations between concept nodes that already have well-specified meanings can be called *horizontal associations*. For example, the concept nodes in Figure 1-1 have an established meaning: they represent the individuals in the small group. The horizontal associations provide additional information about these individuals—who they interact with and how frequently—but the referential meaning of each node (that is, what each node represents) has been specified independent of the strength or nature of these horizontal associations. In classical Pavlovian conditioning a tone (conditioned stimulus, or *CS)* regularly preceded a shock (unconditioned stimulus, *US*). Pavlov assumed that this strengthened a horizontal association from the *CS* node to the *US* node in the brain, and that the strengthening of this horizontal association allows the organism to activate the *US* node when the *CS* node is activated and therefore to predict the occurrence of the *US*. Presumably strengthening such a horizontal association does not change the referential meaning of either the *CS* or *US* nodes—they still represent the same events.

In addition to horizontal associations, human beings and other higher vertebrates possess the ability to form a powerful second type of association: the vertical or chunking association. In one of the most influential papers so far written in cognitive psychology, George Miller drew attention to a process by which human beings recode several elements (attributes or concepts) into a single new element, called a *chunk.*[6] The clearest example of chunking given by Miller concerns the recoding of binary numbers into decimal numbers. The binary system uses only the digits 0 and 1, and recoding from binary into decimal (or octal) works as follows: 000 = 0, 001 = 1, 010 = 2, 011 = 3, 100 = 4, 101 = 5, 110 = 6, 111 = 7. This system recodes three symbols (chunks) into one symbol (chunk), thereby reducing the number of chunks but preserving all the information. Subjects in a memory span test were required to recall a sequence of binary numbers. Those who knew how to use the binary-to-decimal recording scheme nearly tripled their memory spans. Miller pointed out that memory span is primarily a matter of the number of chunks we can recall, regardless of the amount of information contained in each chunk.

Concept Learning

We use the chunking process whenever we attach labels to new events, concepts, or sets of concepts. The dictionary contains hundreds of thousands of words whose meanings can be expressed with phrases or sentences of other words, but the single-word designation is more efficient. Mathematicians and scientists frequently invent new concepts to stand for long sequences of previously defined concepts. This practice is essential for the codification and manipulation of complex subject matter.

The ability to define a new concept to stand for a combination of previously defined concepts appears to require an extension of associative memory. One possible theory assumes that associative memory contains a large pool of previously unspecified elements (nodes), each of which has weak connections to other elements. When one attempts to chunk a set of these nodes, one unspecified node will have maximum strength of direct or indirect connection to this set of already defined nodes. This new node will be maximally activated by the simultaneous activation of its constituents, and the strength of association from these constituents to the new *chunk node* will be strengthened by this simultaneous activation. In this way a new element of the system can come to stand for some combination of old elements.

Such an association of component nodes to a superordinate chunk node is *vertical association,* and it is a different process from the more common *horizontal association* in which already defined nodes are associated to each other by contiguous activation. An example of vertical vs. horizontal associative encoding is shown in Figure 1-2 for the word *cat.*

A chunk node also serves as an intervening node, in that it indirectly

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[6] G.A. Miller, "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information." *Psychological Review,* 1956 (63), 81-97

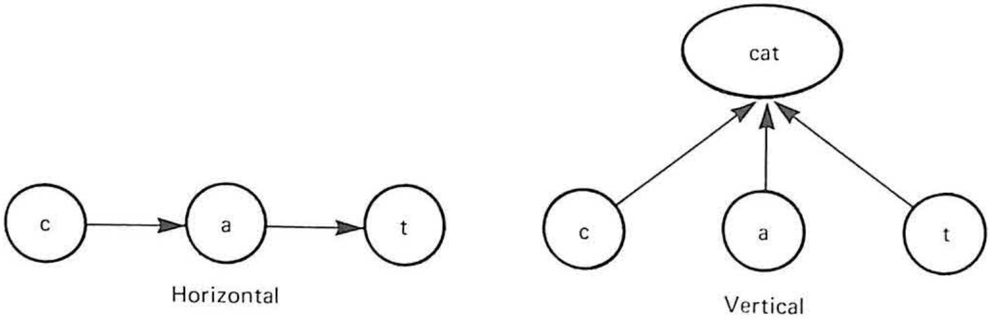

Figure 1-2. Horizontal versus vertical associative memory for the word *cat*. In the horizontal associative memory the associations encode the ordering of the letter constituents. In the vertical associative memory the associations encode the constuency (part-whole) relation between the word and its component letters, which in effect defines the word node as the combination of its letter constituents.

connects the nodes being chunked. Human memory probably has an enormous number of nodes that represent all the concepts and principles we learn, and it seems unlikely that every pair of nodes has a *direct* connection between them, but instead that two memory nodes generally require *indirect* connection through at least one intervening node. Chunk nodes make these indirect connections and have other useful properties as well.

Genetically specified vertical associations are an important part of associative memory. As we discussed previously, the simple line detectors in the visual cortex appear to be specified by associations from a linear set of lower-level spot detectors. The more of these spot detectors that are activated by visual stimulation, the greater the activation of the higher-order line detector via the vertical associations. The assumption of *learned* vertical associations established by the chunking process simply extends this notion. Since the number of concepts (chunks) that human beings appear capable of learning appears to be infinitely large, it is clear that we cannot have innate specification of every node. However, since the number of concepts we do learn is finite, we may assume specification of nodes by learning, and the chunking process is one plausible way to accomplish it.

Semantic memory

In addition to explaining an important part of elementary concept learning, chunking and vertical association also permit specific-element encoding of higher-order conceptual compounds and propositions.[7] Elementary

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[7] J.R. Anderson and G.H. Bower, *Human Associative Memory*. Washington, D.C.: Winston, 1973. W.A. Wickelgren, "Subproblems of Semantic Memory: A Review of *Human Associative Memory*" (by J.R. Anderson and G.H. Bower). *Journal of Mathematical Psychology*, 1976 (13), 243-68.

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concepts, which are often signalled by single words (*dog, he, run, blue, in*) or short phrases (*the girl, a boat*), form the basic nodes of semantic (meaningful) memory. Our knowledge of the world requires the encoding of these elementary concepts into higher-order combinations or conceptual *compounds* (signalled by phrases such as *in Amazon Park, hit the ball, slid downhill,* etc.) and *propositions* (signalled by clauses and sentences such as *Ingrid often plays in Amazon Park, Abe hit the ball,* etc.). In this section we shall compare a horizontal associative minimemory with a vertical associative minimemory for two propositions.

A simple horizontal associative memory for two propositions (*Sharks live in seas, sunfish live in lakes.*) is illustrated in Figure 1-3. The memory in Figure 1-3 is associative because every concept is represented by one specific element. It is horizontal because the contiguous concepts in each sentence have horizontal associations between them (represented by arrows). Such a horizontal associative memory is inadequate because it is subject to associative interference. For example, we could just as easily retrieve the false statements (*Sunfish live in seas, Sharks live in lakes*) as the correct ones.

The vertical associative memory illustrated in Figure 1-4 uses specific nodes to represent elementary concepts, significant conceptual compounds (phrases) in both propositions, and for the propositions themselves. Associations are used to encode the constituents (components) of higher-order nodes, rather than to encode temporal sequence. To retrieve a proposition from this network, one starts at a propositional node (one that has only incoming arrows) and retrieves its subject and predicate constituents, then retrieves their constituents, and so on, until one reaches the elementary concepts. (One also needs some simple grammatical rules to achieve the desired sequential ordering of the concepts, but this is a secondary problem and beyond the scope of this text.) The important thing to note is the way this vertical associative memory reduces associative interference in retrieval

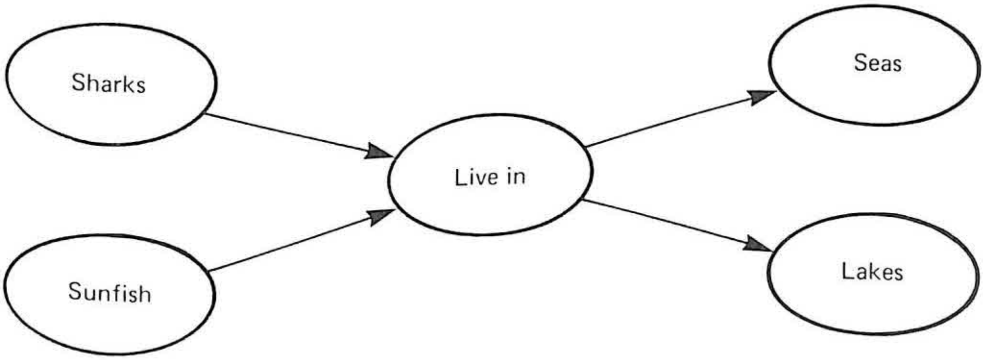

Figure 1-3. A simple (and inadequate) example of a horizontal associative memory for two propositions. Concepts are represented by specific elements, and the sequence of concepts is represented by unidirectional associations (arrows).

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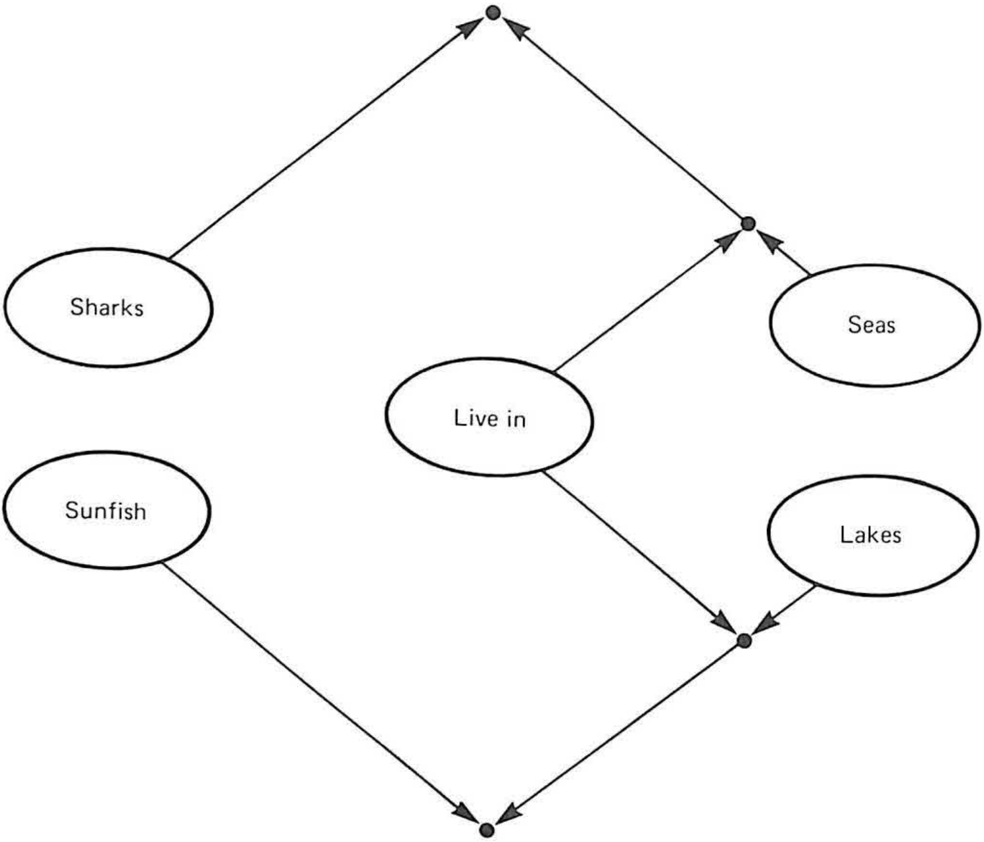

Figure 1-4. A vertical associative memory for two propositions. Elementary concepts and higher-order concepts (phrases and propositions) are both represented by specific elements. Vertical associations are used primarily to encode the components of a higher-order concept rather than to encode temporal sequence.

and thus permits only correct propositions to be retrieved from memory.

The concepts of chunking and of associative versus nonassociative memory are central to an understanding of a wide variety of learning and memory phenomena, from human semantic memory to the primitive learning mechanisms of sensitization and habituation.

DIMENSIONS OF LEARNING

The two types of memory we have considered so far—(the fully associative memory system characteristic of human conceptual memory and the nonassociative system characteristic of visual adaptation and persistence of vision)—have perhaps the greatest functional differences. Most memory lies somewhere between these extremes. Sometimes it is impossible to make behavioral distinctions between changes in the degree of activation or fatigue of elements and changes in the strengths of connections between elements. Consider a simple nervous system consisting of a set of straight-through reflex connections, that is to say, a series of one-to-one associations between sensory neurons and motor neurons. If there is but one sensory neuron that can activate a particular motor neuron, a change in that motor neuron's state of adaptation (fatigue) could be functionally indistinguishable from a change in the strength of the connection between the sensory neuron and the motor neuron.

As nervous systems increase in complexity, and genetic specification relaxes its tight grip on the control of behavior, a greater variety of learning is possible and the functional differences between changes in elements and changes in connection become more visible. In the rest of this chapter we shall discuss several concepts that are important for understanding the different types of learning that we consider in other chapters.

Emission and Omission

Emission training is learning in which a particular response or set of responses is increased in frequency as the result of a learning experience. That is, the learning increases the frequency of the response. In *omission training* a particular response or set of responses is reduced in frequency as a result of the experience. Rewarding a response is emission training, and punishing a response is omission training. Rewarding the suppression of a response is also omission training, while punishing an organism unless it makes a response (escape and/or avoidance) is emission training.

Appetitive and Aversive

The occurrence and suppression of a response can both be reinforced by providing an organism with some positive reward. Such positively motivated or rewarded learning is called *appetitive,* (from the word *appetite*), because the motivational system involved in the reinforcement is a positive appetite or desire to achieve some goal. Learning can also be motivated by the desire to avoid negative consequences, such as extreme cold, heat, pain, fear, and the like. Such negatively motivated learning is termed *aversive.* The relation between motivation and learning is very important, and Chapters 5 and 6 will be devoted to this topic.

Contingencies

Changes in the nervous system (learning) that result from the repeated occurrence of a single event (single-contingency learning) are simpler forms of learning than changes that require the combined (paired or correlated) occurrence of two different events (two-contingency learning). Repeated presentation of a single stimulus may produce *habituation*, which is a reduction in the probability of a reaction to the stimulus. Repeated presentation of other kinds of stimuli may excite the organism and so increase the amplitude or the probability of a reaction to a subsequent occurrence of the same stimulus or to a wide range of other stimuli. This process is called *sensitization*. Habituation and sensitization are examples of single-contingency learning in that they depend or are contingent upon the occurrence of single events.

By contrast, classical conditioning is two-contingency learning, because it is contingent upon the combined occurrence of two events. In classical conditioning a conditioned stimulus (*CS*), such as a tone, is presented just before an unconditioned stimulus (*US*), such as food placed in the mouth, which innately evokes an unconditioned response (*UR*), in this case salivation. After a number of pairings of the *CS* and *US*, the organism demonstrates that it has learned the association between the *CS* and *US* by performing a conditioned response (*CR*) to the *CS* in the absence of the *US*. In this case the *CR* would also be salivation, but not all *CR*s are identical to *UR*s.

Acceptable demonstrations of classical conditioning require the use of control groups to be sure that the changes observed in the probability of the *CR* in response to the *CS* are not the result of single-contingency learning from either repeated presentation of the *CS* alone (habituation control) or repeated presentation of the *US* alone (sensitization control). Sometimes it is desirable to have a combined habituation and sensitization control group that receives both the *CS* and *US* as often as the classical conditioning group, but in an unpaired manner—that is, the *CS* does not regularly precede the *US* by a short fixed time. Table 1-1 illustrates the classical conditioning, *CS* habituation, *US* sensitization, and unpaired control groups.

Instrumental conditioning is three-contingency learning, because it requires the combined occurrence of three events. Any event that learning depends on will be called a *contingency*, because learning is contingent on the occurrence of that event (usually accompanied by other events). For example, when a stimulus (a red light) occurs, the organism must make a response (pressing a bar) to obtain reinforcement (food). The three contingencies are the stimulus, the response, and the reinforcement. In instrumental conditioning, the reinforcement must usually follow the response reasonably quickly for learning to occur.

The types of learning considered in Chapters 2, 3, 4, and 7 are roughly ordered by complexity as measured by the number of contingencies. Chapter 2 considers types of learning that depend upon a single contingency or are highly constrained forms of two-contingency learning. Chapters 3 and

Table 1-1. A small sample of the sequences of events for a classical conditioning group and three control groups: *H* (habituation) of the original response (not the *CR*) to the *CS* owing to repeated presentation of the *CS* (which might be accompanied by sensitization of the *CR* to the *CS*). *S* (sensitization) of the *CR* to the *CS* owing to repeated presentation of the *US*, and the explicitly unpaired control group, which receives both the *CS* and *US* as often as the classical conditioning group, but in an unpaired manner, so that the *CS* does not predict the *US*. To demonstrate classical conditioning, it must be shown that the contingent (paired) occurrences of two events, the *CS* and the *US*, produce a greater increase in the frequency of performing some *CR* to the *CS* than the occurrences of either single event or the unpaired (noncontingent) occurrences of both events.

Group	*Training Events*									*Test*
Classical Conditioning	*CS*	*US*	*CS*	*US*			*CS*	*US*	. . .	*CS*
H Control	*CS*		*CS*				*CS*		. . .	*CS*
S Control		*US*		*US*				*US*	. . .	*CS*
Unpaired Control	*US*		*CS*	*CS*	*US*	*US*		*CS*	. . .	*CS*

4 consider classical and instrumental conditioning, which depend on two or three contingencies. Chapter 7 considers the most complex forms of learning demonstrable in animals other than human beings.

Temporal Contiguity

Temporal contiguity has to do with how close together in time events occur. The degree of temporal contiguity of two events is important only for those types of learning that involve two or more contingencies. Most forms of associative learning are greatly facilitated by a high degree of temporal contiguity, but some forms of associative learning are vastly less fussy regarding temporal contiguity. No form of truly associative learning is totally independent of temporal contiguity, but some forms produce strong associations even when there are delays between the two contingencies on the order of hours. A notable example of this is the development of food preferences and aversions based upon pleasant or unpleasant consequences following ingestion.

Generality and Preparedness

In human conceptual learning any set of two or more contingencies up to the unknown learning capacity of human beings can apparently be associated, probably by use of vertical chunking associations. Not all pairs of events are equally easy to associate, but human conceptual memory appears to have the capacity to associate any concept with any other concept. This does not mean that humans are capable of associating *any* two elements in their nervous systems. The associative generality principle of human conceptual associative memory probably does not hold for lower-level perceptual, motor, emotional, and autonomic learning. Furthermore, the statement that any node in the conceptual memory system can be associated with any other node does not imply that the mind can form associations of unlimited complexity, or that it can form associations that are in some sense conflicting, such as where the learning of one requires the unlearning or weakening of another. Even so, human conceptual memory demonstrates an enormous degree of generality in its capacity to associate, because there is within it little innate bias for learning particular associations and not others.

By contrast, as Garcia, Seligman, Bolles, and others have demonstrated, virtually all forms of animal and lower-level human learning show substantial amounts of *preparedness* or readiness to learn some associations and *contrapreparedness* for others.[8] Both human beings and animals are especially prepared to associate the tastes and odors of new foods with nausea. We are not so prepared, and many animal species are contraprepared, to associate various environmental cues with subsequent nausea.[9] The most highly prepared associations are but one step away from conversion into the organism's genetic specification. An organism whose connections are not totally set genetically can exhibit some flexibility in adapting to changing environments even when the potentially learnable associations are greatly restricted. The phylogenetic development of learning capacity has to do with an increase in the degree of interconnection of elements in the nervous system and a greater generality of potentially learnable associations, which means a lower degree of preparedness to learn particular associations.

Critical Periods

Most forms of learning can occur throughout the life of the organism (though learning is usually poorer in very young and very old organisms), but some forms of learning are greatly facilitated when they occur during certain critical periods. The best-known example of this is *imprinting* in baby chickens, ducks, and geese. A day or so after birth the young bird will look for, be attracted to, and follow virtually any moving object in its environment. Typically this is the mother, but if the mother is absent, the young bird will imprint on some other object or organism, and thereafter will continue to be attracted to this object or organism. This type of learning occurs during a very limited critical period following hatching, and is difficult or impossible to produce or to reverse at any other time.

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[8] J. Garcia, B.K. McGowan, and K.F. Green, "Biological Constraints of Conditioning," in A.N. Black and W.F. Prokasy (eds.), *Classical Conditioning II: Current Theory and Research.* Englewood Cliffs: Prentice-Hall, 1972. M. Seligman, "On the Generality of the Laws of Learning." *Psychological Review,* 1970 (77), 406-18. R. Bolles, "Species-Specific Defense Reactions and Avoidance Learning." *Psychological Review,* 1970 (77), 32-48. Also see M.E.P. Seligman and J.L. Hager (eds.), *Biological Boundaries of Learning.* Englewood Cliffs: Prentice-Hall, 1972.

[9] J. Garcia and R.A. Koelling, "Relation of Cue to Consequence in Avoidance Learning." *Psychonomic Science,* 1966 (4), 123-24.

Critical periods that are like if not the same as imprinting may take place periodically throughout the life of an organism. For example, the digger wasp appears to make a careful visual survey of its burrow-nest each time it leaves.[10] If a distinctive visual stimulus, such as a ring of pine cones, is placed around the nest and then is moved a short distance away after the wasp leaves, the wasp will return to the ring of pine cones rather than to the original nest location. If this is imprinting (and it is not clear that it is), then the critical period occurs every time the wasp leaves the nest. Such critical periods might be referred to as *triggered.* In this case the triggering could be from either the central motor program that controls leaving the nest or the stimuli associated with leaving.

Dynamics

It is important to know how quickly a particular type of learning is forgotten—within seconds, minutes, hours, days, months, or years. It is also important to know the subsequent experiences that accelerate or retard forgetting. Thus, the laws and rates of storage dynamics (forgetting) and the dynamics of learning and retrieval are important for distinguishing different types of learning.

SUMMARY

1. Memory has limited capacity. Quality of knowledge should be emphasized more than quantity.
2. Learning is measured by changes in performance, but performance depends on motivation and attention.
3. *Memory trace* refers to any change in the nervous system that is a result of some learning experience.
4. The three phases of memory are acquisition (learning), storage (retention as affected by rehearsal, consolidation, and forgetting), and retrieval (recognition and recall).
5. Events are encoded in long-term memory by means of general concepts, not by recording all the sensory-motor details of our experiences.
6. A nonassociative memory consists of a set of locations that contain the patterns representing the concepts used to encode an event. Temporal

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[10] N. Tinbergen and W. Kruyt, "Uber der Orientierung des Bienenwolfes (*Philanthus triangulum* Fabr.)." III. Die Bevorzugung bestimmter Wegmarken. *Z. vergl. Physiol.*, 1938 (25), 292-334. G. van Beusekom, "Some Experiments of the Optical Orientation in *Philanthus Triangulum* Fabr." *Behavior,* 1948 (1), 195-226.

order is represented by storing the events in a fixed order of locations. Locations are directly accessible, but accessing (finding) events or concept representations generally requires a search of some set of locations.

7. An associative memory consists of a set of elements (nodes) each of which is the unique representation of a concept. An event is represented by activation of a set of nodes. Event representations are directly accessible, obviating the need for search in most cases.
8. Chunking is the formation of vertical associations to specify a new node—the chunk node—that represents a combination of old nodes. Chunking may be an essential part of concept learning and may play an important role in the way we represent propositions in semantic memory.
9. Some important concepts used to analyze and classify types of learning include:

   (1) whether the learning is emission or omission training, (2) whether the motivation is appetitive (positive) or aversive (negative), (3) the number of contingencies (events upon which learning is contingent), (4) the degree of temporal contiguity (closeness in time) of contingent events when two or more contingent events are required, (5) the preparedness of the organism for some type of learning, (6) the dependence of learning on a critical period, and (7) the dynamics (rate) of learning and forgetting.

2 Prepared Learning

OBJECTIVES

1. To describe the following single-contingency types of learning: (1) *sensitization* (an increased tendency to emit certain responses, largely to mild warning signals), (2) *habituation* (a reduced tendency to emit certain responses to mild warning signals), (3) *imprinting* (the attachments that young birds form to parents during a critical period shortly after hatching), and (4) *prepared sensory-motor learning* such as pecking or song learning in birds.
2. To discuss whether these forms of single-contingency learning are associative or nonassociative, concluding tentatively that even sensitization and habituation probably result from changes in the strength of associations.
3. To demonstrate that an organism can exhibit substantial differences in *preparedness* (*readiness*) for different types of learning.
4. To describe in some detail how organisms acquire aversions and preferences for food.

In this chapter we look at some of the most tightly constrained types of learning: sensitization, habituation, imprinting, prepared sensory-motor learning, and prepared conditioning. Sensitization, habituation, imprinting, and some highly prepared sensory-motor learning are types of learning that depend upon the occurrence of a single event or contingency rather than on a pairing or correlation of two or more events. Single-contingency learning almost necessarily exhibits a considerable degree of genetic constraint (preparedness)—that is to say, only certain types of events produce the changes in behavior, and only a restricted range of behaviors can be affected by the learning process. In highly prepared associative learning, organisms have been genetically biased to learn certain types of associations, and the role of experience is limited to the differential strengthening or weakening of one out of a restricted range of possible associations.

SENSITIZATION

You are walking through an old, abandoned house that is full of cobwebs and spiders, and you feel a light tickle on your ear. Perhaps it is your own hair, but if, like many people, you are somewhat afraid of spiders, you will probably make a startle response—perhaps a swipe at your ear with your hand. The same stimulus in your own home or on a city street would not evoke such a reaction. This effect of environmental stimuli to enhance the probability or magnitude of particular reactions is an elementary learning process called *sensitization.* Much sensitization is short term: you would not be likely to exhibit the same startle reaction an hour later in your own home, but you might still exhibit the reaction five minutes after leaving the old house.

Sensitization refers to an increase in the frequency or amplitude of some response to a stimulus as a consequence of presentation of either that stimulus or, more frequently, some other stimulus. Higher organisms typically demonstrate sensitization when they become "jumpy" in response to repeated presentation of strongly aversive stimuli—stimuli that are either painful or fear arousing. This sensitization is demonstrated by an increased response to what might be called mild warning or arousing stimuli. For example, repeated administration of electrical shock to an organism will frequently produce enhanced emotional arousal reactions, orienting reactions, and even gross bodily movement reactions to sudden, but neutral, stimuli such as tones and flashing lights.

Sensitization is an important potential confounding factor that must be controlled in classical conditioning. In classical conditioning the pairing of a conditioned stimulus (*CS*), such as a tone, with an unconditioned stimulus (*US*), such as a shock, eventually produces the conditioned response (*CR*), such as leg flexion, to the conditioned stimulus. However, to demonstrate classical conditioning, the change in behavior must result from a *pairing* of two events, that is to say, two contingencies are necessary, not one. Sensitization is a single-contingency form of learning. As we have noted, repeated presentation of a strong stimulus like a shock might be sufficient in and of itself to produce a reaction such as leg flexion the very first time the tone was presented, independent of its pairing with the shock. In classical conditioning it is necessary to include a sensitization control condition, by presenting the *US*—the shock—many times without pairing it with the *CS*. One must show that the paired *CS-US* condition produces either a different *CR* or a different magnitude or frequency of *CR* than the unpaired presentation of the *US* alone. Sensitization within a classical conditioning paradigm is frequently referred to as *pseudoconditioning*.

Sensitization in one form or another can probably be demonstrated in virtually every species of the animal kingdom, including single-celled organisms. Of course the mechanisms that produce sensitization in animals that do not have nervous sytems must differ from the mechanisms that produce sensitization in animals with nervous systems. Furthermore, nervous systems of different complexity and basic structural organization may also have different sensitization mechanisms.

Nevertheless, it can be very instructive to study sensitization in lower species whose simpler or more accessible nervous systems permit more precise study of the neural mechanisms underlying the phenomenon. The work of Eric Kandel and his colleagues on the functional properties and neural mechanisms of sensitization and habituation in the sea slug *Aplysia* is of particular interest. Pinsker, Hening, Carew, and Kandel investigated the siphon withdrawal reflex in response to light touch.[1] They demonstrated that the duration of this defensive reflex could be substantially lengthened by the repeated prior presentation of electric shock. Administration of electric shock four times a day for four days produced sensitization effects that were still present three weeks after the end of shock administration. Retention of sensitization did decline progressively from one day to one week to two weeks, but there was still some sensitization of the reflex after three weeks, indicating very long-term retention under these conditions.

A reflex might be sensitized through an effect on the sensitivity of the sensory or motor neurons, and not on the connections between them. In a system with only one-to-one connections between sensory and motor neurons, such effects would be indistinguishable from the effects on the efficacy of connections. That is to say, if the only function of some sensory neuron is to signal a response, then a change in the sensitivity of that neuron or its rate of background firing cannot be distinguished functionally from a change in the efficacy of its connections to the motor response unit. Similarly, for a motor unit whose only input comes from a single sensory neuron, a change in the sensitivity of that motor neuron or its background firing rate is functionally indistinguishable from the changes in the strength of connection from the sensory neuron to the motor neuron.

However, whenever there is a greater degree of convergence and divergence of connections within some nervous system, one can in principle functionally distinguish changes in the strength of associations from changes in sensitivity or rate of firing of elements. For example, it is unlikely that your sensitized reaction to the tickle stimulation was the result of an increase in the sensitivity of the touch receptors in your ear (though conceivably this could have been a component of the process). Under other conditions you might have responded to the tickle by scratching your ear rather than taking a swipe at it, but particular reactions were more sensitized than others because sensitization changed the rank ordering of probabilities of various responses. Such effects are unlikely to be caused by a change in the sensitivity of the sensory neurons. Similarly, the probability that you would swipe at your ear was not increased to every type of stimulus, but only to tactile stimulation of the ear. In this case it is possible that the threshold for emitting all swiping reactions was reduced, but the only stimulus whose strength of connection to an ear swiping response was high enough to evoke it was tactile stimulation of the ear. In most examples of habituation, no careful studies have yet appeared that rule out peripheral sensory and motor neuron sensitivity changes in sensitization, but they are possible in principle. If such a locus were ruled out, then the effects of sensitization would be on the strength of connections, which would make sensitization a form of associative memory, even though from a functional viewpoint it depends upon the occurrence of a single event and not on the pairing of two or more events. Thus, sensitization might either be a form of associative memory or nonassociative memory. Figure 2-1 illustrates both the associative and nonassociative interpretations of sensitization.

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[1] H. Pinsker, W. Hening, T. Carew, and E. R. Kandel, "Long-Term Sensitization of a Defensive Withdrawal Reflex in *Aplysia*." *Science*, 1973 (182), 1039-42.

In terms of the previously discussed dimensions of learning, sensitization is emission training in that it involves an increase in the probability of some

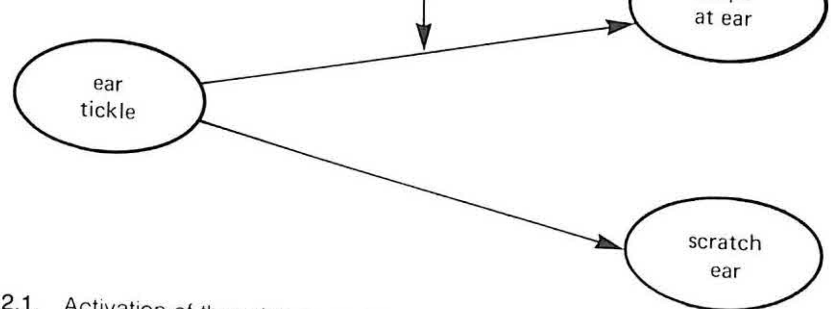

Figure 2.1. Activation of thoughts associated with spiders, such as cobwebs, produces sensitization of either the association from the sensation of ear tickle to the response of swiping at the ear (an associative memory trace) or else sensitizes all swiping responses, including swiping at the ear (a nonassociative memory trace).

response or set of responses. In principle, it might be either appetitively or aversively motivated, though the typical examples are aversive. If the sight of food to a hungry animal led to salivation in response to a previously neutral tone, then such a sensitized response would be an example of appetitively motivated sensitization. Since sensitization is produced by a single contingency, contiguity of two contingencies is obviously irrelevant. Generality of connection definitely does not hold for sensitization, since the *S-R* connections being sensitized already exist, but can have their strength of association increased or decreased. There is usually a substantial genetic predisposition involved in determining which connections can be sensitized. Sensitization has not been shown to occur preferentially during any critical period.

Finally, some sensitization processes last no longer than a few seconds while others can be quite long term, even for an invertebrate mollusc, as we have seen. Carew and Kandel speculate that chronically high levels of arousal or anxiety in human beings might result from sensitization, though they acknowledge that this is only a possibility based on a rough analogy to the long-term sensitization process they have studied.[2]

An example of long-term sensitization in human beings is the enhanced sensitivity to distress calls of parents who are responsible for newborn babies. Anecdotally at least, such a parent will be far more likely to awaken in the middle of the night in response to the child's crying than will another adult without such responsibility.

HABITUATION

You decide to save money be taking an inexpensive apartment whose most distinguishing feature is that the tracks of an elevated commuter train run about eight feet from the bedroom window. At first you notice the train every time it goes by, particularly when you are trying to get to sleep, but several weeks later you frequently fail to notice when the train goes by (though your guests still notice and wonder how you can live in such an apartment). The reduction in the frequency and intensity of your arousal and orienting reaction to the noise is an example of habituation. This process is not the same as sensory adaptation, because the activity of peripheral auditory sensory neurons is relatively or completely unaffected. (We do have a very modest capability, via contraction and relaxation of middle-ear muscles, to adjust the peripheral auditory sensitivity by approximately ten decibels, but this capability is too small to fully account for habituation to frequently occurring irrelevant sounds.)

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[2] T. J. Carew and E. R. Kandel, "Synaptic Analysis of the Interrelationships Between Behavioral Modifications in *Aplysia*," in M. V. Bennett (ed.), *Synaptic Transmission and Neuronal Interaction*. New York: Raven Press, 1974, pp. 339-83.

At one time it was thought that such habituation was produced by a process known as sensory gating wherein feedback from higher levels of the nervous system would actively inhibit the response of the peripheral auditory neurons to auditory input. However, careful studies of the physiological correlates of habituation to auditory stimuli have demonstrated that no such peripheral sensory gating occurs.[3] The locus of various attentional changes, including habituation and distraction, is at much higher levels, such as the auditory cortex.[4]

Almost any change in the characteristics of a habituated stimulus is frequently sufficient to restore part or all of the initial response.[5] This is particularly true when the intensity of the stimulus is increased, but it can also happen when there is a decrease in the intensity, even without a change in quality.[6] Changes in the location of a stimulus can reduce habituation,[7] and qualitative changes in a stimulus can reduce or eliminate habituation completely.[8] Finally, habituation to a compound stimulus may transfer incompletely or not at all when the components of the compound stimulus are presented in isolation.[9] Thus, habituation is extremely selective on the stimulus side in ways in which adaptation is not.

Habituation of Orienting Responses

When an unexpected (warning) stimulus is presented to a mammal, the animal will often make an *orienting response*. Orienting responses consist of any or all of the following components: (1) a startle reflex; (2) an observing response involving bodily movements, eye movements, ear movements, sniffing, and the like that results in better reception of the stimulus by the relevant sense organs; (3) an increase in arousal as indicated by respiration, heart rate, vascular responses, the galvanic skin response (GSR), measures of brain activity by the electroencephalogram (EEG), and other symptoms; and (4) a heightened readiness to perform certain fight or flight responses.[10] The components of the orienting response decrease in probability and intensity with repeated presentation of the warning signal, that is to say, the orienting response to this stimulus habituates.

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[3] F. G. Worden and J. T. Marsh, "Amplitude Changes of Auditory Potentials Evoked at Cochlear Nucleus During Acoustic Habituation." *Electroencephalogram and Clinical Neurophysiology*, 1963 (15), 866-81. W. O. Wickelgren, "Effect of Acoustic Habituation on Click-Evoked Responses in Cats." *Journal of Neurophysiology*, 1968 (31), 777-84. F. G. Worden, "Auditory Habituation," in H. V. S. Peeke and M. J. Herz (eds.), *Habituation*. Vol. 2. New York: Academic Press, 1973, pp. 109-37.

[4] W. O. Wickelgren, "Effect of State of Arousal on Click-Evoked Responses in Cats." *Journal of Neurophysiology*, 1968 (31), 757-68. W. O. Wickelgren, "Effects of Walking and Flash Stimulation on Click-Evoked Responses in Cats." *Journal of Neurophysiology*, 1968 (31), 769-76. Wickelgren, "Effect of Acoustic Habituation on Click-Evoked Responses in Cats."

[5] G. Razran, *Mind in Evolution*. Boston: Houghton Mifflin, 1971, pp. 29-57.

[6] O. S. Vinogradova and D. E. Lindsley, "Single-Neurone Extinctions of Reactions to Sensory Stimuli in the Unanesthetized Visual Cortex of the Rabbit." *Zhurnal Vysshey Neronoy Deyatel'nosti imeni I. P. Pavlova*, 1963 (13), 207-17.

[7] K. H. Eikmanns, "Verhaltensphysiologische Untersuchungen uber den Beutefang und das Bewegungssehen der Erdkrote (*Buf bufo* L.)." *Tierspsycholo.*, 1955 (12), 229-53. See also the review by D. A. Goodman and N. M. Weinberger, "Habituation in 'Lower' Tetrapod Vertebrates: Amphibia as Vertebrate Model Systems," in Peeke and Herz, *Habituation*, Vol. 1, p. 92.

[8] Razran, *Mind in Evolution*.

[9] T. Engen and L. P. Lipsitt, "Decrement and Recovery of Responses to Olfactory Stimuli in the Human Neonate." *Journal of Comparative and Physiological Psychology*, 1965 (59), 312-16.

The waning of the orienting response is not the result of motor fatigue, since other novel stimuli can still evoke a full-blown orienting response. Neither is it a consequence of sensory adaptation, since presentation of a stimulus qualitatively identical to the habituated stimulus but at a lower intensity or different location will partially restore the orienting response. Even slight changes in the stimulus are sufficient to restore the orienting response. Sokolov points out that it is as if the nervous system knows what stimulus to expect and has habituated the response to the expected stimulus.

Furthermore, once there has been habituation of the orienting response, to one stimulus, presentation of a different warning or danger stimulus will restore much of the orienting response to the previously habituated stimulus. This phenomenon is known as *dishabituation*. Dishabituation provides yet another reason for distinguishing habituation from either sensory adaptation or motor fatigue.

Very young infants can be conditioned only with great difficulty, if at all, but they frequently demonstrate substantial capacities for habituation of the orienting response.[11] Such infants will look at a stimulus the first time it is presented, but the frequency of looking at the same stimulus decreases with repeated presentation, as the stimulus becomes more familar. Arousal and startle responses to sudden auditory stimuli also habituate in infants.

Habituation of Withdrawal Responses

Habituation is probably found in every species of the animal kingdom, in one form or another, though the mechanisms exhibit substantial variation.[12]

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[10] E. N. Sokolov, "Neuronal Models and the Orienting Reflex," in M. A. B. Brazier (ed.), *The Central Nervous System and Behavior*. New York: Josiah Macy, Jr. Foundation, 1960, pp. 187-276. E. N. Sokolov, "Higher Nervous Functions: The Orienting Reflex." *Annual Review of Physiology*, 1963 (25), 545-80. E. N. Sokolov, *Perception and Conditioned Reflex*. New York: Macmillan, 1963.

[11] See review by H. R. Schaffer, "The Multivariate Approach to Early Learning," in R. A. Hinde and J. Stevenson-Hinde (eds.), *Constraints in Learning*. Englewood Cliffs: Prentice-Hall, 1973.

[12] G. Humphrey, *The Nature of Learning in Its Relation to the Living System*. New York: Harcourt, Brace, 1933. See also W. H. Thorpe, *Learning and Instinct in Animals*. Cambridge: Harvard University Press, 1963.

As an example of habituation below mammals let us once again consider the siphon withdrawal reflex of the sea slug *Aplysia* studied by Kandel and his associates. This reflex can be habituated by repeated presentation of a light tactile stimulus. A single training session of ten tactile stimuli produces habituation of siphon withdrawal that recovers spontaneously after periods ranging from minutes to hours, but repeated training sessions produce extremely long-lasting habituation, especially when there is substantial temporal spacing between the sessions. Ten training trails a day for four days can produce habituation that persists to a diminishing extent for over three weeks before spontaneous recovery is complete.

Spontaneous recovery is but one way in which a reflex pathway can recover from the effects of habituation. The other way is *dishabituation.*[13] Dishabituation often involves presentation of a warning signal that increases the responsiveness of the organism to previously habituated stimuli. It usually takes [illegible] more than a modest change in the original habituated stimulus to produce dishabituation,[14] but the most effective dishabituating stimuli are typically strong warning signals that evoke intense arousal, orienting, and s[illegible]e responses.[15]

The mechanisms by which such dishabituation counteracts prior habituation are by no means clear in most instances. However, in the case of habituation of the siphon withdrawal reflex in Aplysia, it has been established that the same electric shock that produces sensitization also produces dishabituation, and the magnitude of the shock's effect is in no way affected by whether the stimulation preceded or followed habituation.[16] That is to say, dishabituation appears to be identical to sensitization, since the effects are pretty much independent of whether the sensitizing stimulus preceded or followed habituation. Thus, the mechanisms producing habituation and sensitization (or dishabituation), though substantially independent, are functionally coupled to change the strength of the defensive reflex in a more appropriate and flexible manner than either mechanism would in isolation.

Both sensitization and habituation are essentially single-contingency forms of learning, since the pairing or lack of pairing of the mild and strong warning signals is irrelevant to the net balance between habituation and sensitization. The two mechanisms proceed independently to produce a net result that represents the balance between sensitization and habituation.

Whether dishabituation is always functionally identical to sensitization is by no means established. Habituation in higher organisms may sometimes be functionally analogous to the extinction of an association between the representatives of the mild warning stimulus and danger, as activated by strong warning stimuli. In such cases dishabituation would be a subsequent reconditioning, because it would depend strongly on a temporal pairing of the mild and strong warning stimuli for the dishabituating (reconditioning) effect. However for the siphon withdrawal reflex of *Aplysia* habituation is not extinction, and dishabituation is sensitization, a single-contingency form of learning, not classical conditioning, a two-contingency form of learning.

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[13] See review by R. F. Thompson and W. A. Spencer, "Habituation: A Model Phenomenon for the Study of Neuronal Substrates of Behavior." *Psychological Review*, 1966 (173), 16-43.

[14] See J. A. Deutsch and D. Deutsch, *Physiological Psychology*. Homewood, Ill.: Dorsey Press, 1973, pp. 414-416.

[15] Humphrey, *The Nature of Learning*.

[16] Carew and Kandel, "Synaptic Analysis of Interrelationships."

Habituation and Adaption Compared

Habituation is similar to negative sensory adaptation in that both involve decreased sensitivity, but the two forms of learning are functionally distinct. In the first place, adaptation is almost completely unrelated to any specific motivational or goal system and thus is outside the appetitive or aversive distinction. Habituation typically occurs when a mild warning stimulus is not followed by a strong aversive stimulus. Thus, habituation lies within the sphere of aversively motivated behavior, although the information stored is essentially that a stimulus that *might* be an indicator of danger is not such an indicator in this situation.

Habituation and adaptation, like sensitization, are single-contingency forms of learning, and thus temporal contiguity is irrelevant to both. Habituation is a highly prepared form of learning in that only certain connections habituate, typically those between generalized warning signals and arousal, orienting, and startle responses.[17] However, the change is probably in the association between stimuli and responses, and in this sense is associative memory, even though it is produced by a single contingency. Neither habituation or adaptation has a critical period so far as we know, since neither is peculiar to certain times in the life span of organisms.

Another difference between habituation and adaptation is that adaptation decreases the sensitivity to a very wide class of stimuli, while habituation is generally for one specific stimulus or for a very small class of highly similar stimuli. Furthermore, sensory adaptation cannot be reversed by presentation of some novel stimulus, while habituation can (dishabituation.)[18]

Finally, adaptation and habituation are different in their dynamic properties. Adaptation is typically limited to relatively short-term effects—tens of seconds to tens of minutes—while habituation can be short term or long term—sometimes lasting many weeks. In terms of acquisition dynamics, adaptation is best produced by relatively continuous exposure to the adapting conditions, whereas habituation can be produced more effectively by periodic repetition of a transient rather than a continuous stimulus, and there can be considerable time between repeated presentations of the stimulus to which habituation is occurring.[19]

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[17] Humphrey, *The Nature of Learning*.

[18] Deutsch and Deutsch, *Physiological Psychology*.

All this does not exclude the possibility that a habituation may be a central form of adaptation, but the locus is more likely in the efficacy of certain synaptic connections. Thus, habituation is almost certainly an associative memory change, albeit a highly prepared one, which, like sensitization, results from a single contingency.

IMPRINTING

The young of most higher animals require the care and instruction of one or both of their parents for some time before they are capable of independent survival. The young of precocial animals are capable of locomotion virtually immediately after birth and so pose a special problem: if such infants are not to wander off and get lost, it is quite functional that they know their parents and be attracted to them. To meet this need, young ducklings, goslings, chicks, and other precocial animals appear to possess a special early learning mechanism known as *imprinting.*[20]

In baby chicks and ducklings, imprinting proceeds approximately as follows. During a period that typically ranges from five to thirty hours following hatching, the young bird looks for, is attracted to, and will actively follow virtually any moving object in its immediate environment. When a choice is available, the young animals prefer to follow objects that are highly similar to adults of the same species, but if nothing better is present, they even will approach a stationary flashing light. The longer-term consequences of exposure to a particular model stimulus during this critical period after birth is that the young animal will become more or less permanently attracted to that model and treat it as if it were its parent. These attachments take place about a day after birth, and it is subsequently difficult or impossible to weaken or reverse this attachment. Baby chicks and ducklings have been imprinted on human beings, wooden models of vari-

[19] H. V. S. Peeke and S. C. Peeke, "Habituation in Fish with Special Reference to Intraspecific Aggressive Behavior," in Peeke and Herz, *Habituation,* Vol. 1, p. 59-83. L. Petrinovich, "A Species-Meaningful Analysis of Habituation," in Peeke and Herz, *Habituation,* Vol. 1, p. 141-162.

[20] The factual data in this section on imprinting come from the following sources: Thorpe, *Learning and Instinct in Animals,* 128-31 and 404-27. W. Sluckin, *Imprinting and Early Learning.* Chicago: Aldine. P. P. G. Bateson, "Internal Influences on Early Learning in Birds," in Hinde and Stevenson-Hinde, *Constraints on Learning,* pp. 101-16. G. Gottlieb, "Imprinting in Relation to Parental and Species Identification by Avian Neonates," in Seligman and Hager, *Biological Boundaries of Learning,* pp. 279-98.

ous kinds, other baby chicks and ducklings, objects emitting auditory call signals of various kinds, and even stationary flickering lights.

Critical Period

The feature that distinguishes imprinting from other types of learning is the existence of an extremely brief and well-defined *critical period* during which imprinting can occur. Figure 2-2 presents a typical function relating the strength of imprinting to the age of the young bird. No other type of learning is limited to so brief a portion of the lifetime of the organism.

The onset of the critical period requires a level of neural maturation that is about the equivalent of the level ducklings achieve six hours after hatching. Since ducklings hatch at various developmental (embryonic) ages after the onset of incubation, it is possible to determine whether it is the developmental age or the age since hatching that is more critical in determining the onset of the critical period for imprinting, and the evidence indicates that for ducklings hatching into a patterned environment it is the developmental age rather than the hatching age (and the associated visual experience) that is more important. It is not yet established whether some

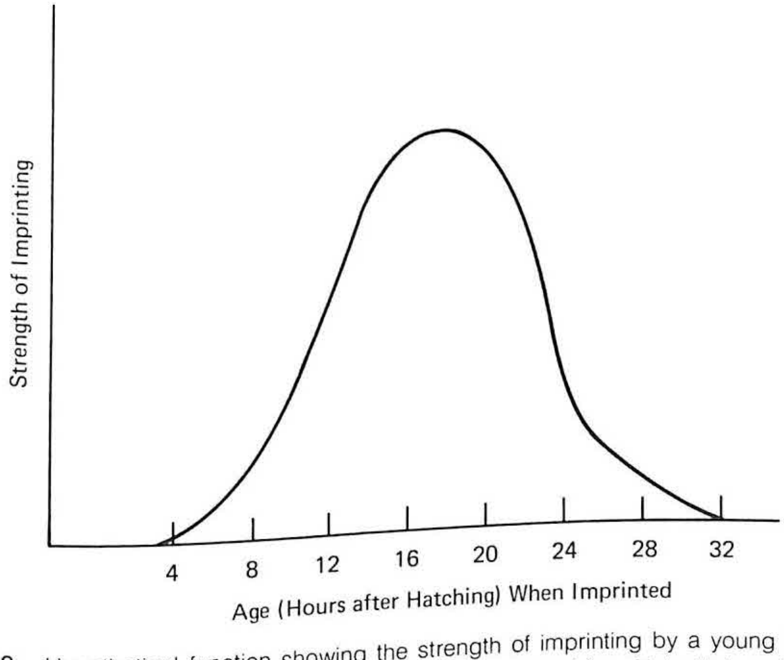

Figure 2-2. Hypothetical function showing the strength of imprinting by a young bird on a model exposed for a fixed period at different ages since hatching. Note that under normal rearing conditions the critical period for imprinting ranges from about 5 to 30 hours after hatching, but when the visual experience of the young bird is greatly restricted, the offset of the critical period can be greatly extended, to a week or longer after hatching.

amount of general visual experience is necessary for imprinting to take place.

The offset of the critical period appears to depend quite sharply on experience, particularly on the occurrence of imprinting itself. Apparently the critical period for imprinting ends when the birds have become satisfactorally imprinted on at least one object. Experiments that have restricted the visual experience of young chicks and ducklings have demonstrated that the duration of the critical period can be extended by several days beyond its normal termination. Social isolation, which eliminates exposure to moving or flashing objects, appears to extend the critical period by as much as a week, and more extreme forms of visual isolation, such as the use of occluders to eliminate pattern vision, might extend the critical period even longer. It is possible that young birds reared in environments without changing objects eventually become imprinted upon some stationary object, and this terminates the critical period. If this is the case, then more complete sensory isolation might extend the critical period for many weeks, but this is not yet known.

Imprintable Stimuli

A very wide range of stimuli appears to be suitable for imprinting, but the extent of this range is not well established. Young birds have a substantial genetic predisposition for imprinting upon objects with visual and/or auditory characteristics that are appropriate to their species. An object that is too small is treated more as a potential food object than as a potential imprinting object. Stimulus change such as flicker (which might be produced by flapping wings) is a desirable visual characteristic. Most desirable of all is movement, because it distinguishes living organisms from nonliving objects. With auditory imprinting the call of the same species is preferred over the call of a related species, which is preferred to very different auditory signals. When the imprinting process begins, the organism shows a very broad generalization gradient for attraction and following, but after imprinting has progressed for about a day this narrows to include only models that are highly similar to the imprinting object.

Following Responses

During the imprinting period the young birds typically follow the most appropriate imprinting object available, and there is some indication that during this period they are including within their concept of the imprinting object a variety of different views of that object. This is functional, since the appearance of a parent from the front may have little in common with the appearance of the parent from the side or the back. Thus, a variety of different stimulus configurations that may have little or nothing in common must be integrated into a common concept of the parental model.

This might explain why imprinting takes several hours to complete rather than being an instantaneous process. Another purpose might be to permit greater choice of the most appropriate imprinting object, since during the critical period, exposure to a less preferred model is relatively easily reversed by subsequent exposure to a more appropriate model.

The critical definition of imprinting is not the following of the young bird that takes place during the critical period, but rather the degree to which following takes place after the critical period is over. That is to say, it is the *transfer* of the following response to subsequent periods in life that is critical for the definition of imprinting, not the innately determined following behavior during the critical period. It has been demonstrated that it is not important for the bird to follow during the critical period for imprinting to occur. Mere exposure of the bird to an appropriate model is sufficient for imprinting, as measured by following behavior after the critical period.

Reinforcement

Imprinting appears to be an example of unreinforced learning, in that extrinsic reward for attending to and following a model during the critical period is both unnecessary and not beneficial to produce imprinting, unlike instrumental conditioning, which these organisms exhibit in the rest of their lives. One can always regard exposure to a suitable imprinting object as reinforcement, but in this case the stimulus eliciting the following response is identical to the reinforcing stimulus, which is certainly different in an important way from reward learning, in which the reward is different from the stimulus that evokes the response.

The best way to consider the role of reinforcement in imprinting is in terms of the framework we have established regarding the number of contingencies necessary for producing a particular kind of learning. Within this framework, imprinting appears to be a single-contingency form of learning, like adaptation, sensitization, and habituation. The following response is not essential to imprinting. Even if one regards the imprinting stimulus as intrinsically reinforcing, the only necessary contingency is exposure to a suitable model.

Irreversibility

The attachment of a young bird can be reversed by exposure to a more suitable model during the critical period itself, but after this period it is extremely difficult if not impossible to reverse the attachment. Competing attachments that develop after the critical period apparently do so by a more conventional form of reinforced associative learning.

Denervation supersensitivity, a phenomenon in the development of synaptic and neuromuscular connections, may play an important role in many forms of learning, including imprinting.[21] If the motor neurons to a muscle are cut, the entire surface where the motor neurons can make contact with the muscle becomes highly sensitive to the neural transmitter (acetylcholine) that motor neurons typically squirt on muscle to cause it to contract. Under ordinary conditions only that portion of the muscle where motor neurons actually make synaptic contact is sensitive to acetylcholine; the rest of the surface is insensitive. As the motor neurons regenerate and make new synaptic contacts with the muscle, the portion of the muscle that is sensitive to acetylcholine gradually becomes restricted once again to the places where the motor neurons make contact, and after a sufficient number of such connections have been made, the rest of the surface loses its sensitivity to the motor neuron input. These sites may well be somewhat different from the sites where they made contact before. Thus, denervation supersensitivity is an adaptive mechanism in that it allows a developing connection to be functional as soon as it is made.

There is evidence that many neurons in the nervous system have large numbers of potential sites for receiving synaptic input. When strong synaptic connections are developed at some of these sites, the remaining portions of the synaptic surface become insensitive to input. Thus, a neuron can have a huge number of potential synaptic connections as a result of the neural maturation process, but selection as to which of these potential connections will become functional is determined by experience.

This neural model appears to fit with many types of learning, including imprinting. Assume that the neurons representing the concept of "parent" have, as a result of neural maturation, a large variety of input synaptic connections from visual and auditory pattern representatives. There are innately determined biases, in that pattern representatives more characteristic of the parents of that species have richer degrees of innate connection to the "parent" concept than pattern representatives less characteristic of the species. However, a rather broad range of sensory feature representatives have some degree of connection, and experience makes the final decision as to which sets of features will become most strongly associated to the parent concept and which others will be functionally disconnected. This neural process of establishing functional synaptic control of a neuron may or may not be reversible for conceptual learning, but it appears to be irreversible for imprinting.

Perceptual Learning and Concept Formation

As previously mentioned, it appears that during the critical period the young bird integrates several views of the model into its concept of the parent. The perceptual learning aspects of this process, as demonstrated through experiments, show that exposure to a particular model during imprinting facilitates later choice learning between this stimulus and a new stimulus to obtain food reward.[22] The positive transfer that occurs as a result of exposure during the critical period obtains whether the familiar object is the rewarded one or the unrewarded one. Thus, it is not the attachment itself that is the basis for the positive transfer, but the perceptual learning of the characteristics of the model.

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[21] For a recent paper that refers to earlier works see S. W. Kuffler, M. J. Dennis and A. J. Harris, "The Development of Chemosensitivity in Extrasynaptic Areas of the Neuronal Surface after Denervation of Parasympathetic Ganglion Cells in the Heart of the Frog. *Professional Royal Society of London*, 1971 (177), 555-63.

When the positive and negative stimuli for the later choice task were both exposed in rapid alternation during the critical period, subsequent discrimination learning between these two stimuli was actually retarded. However, if the bird was exposed to both stimuli during the critical period but was given a half hour with one stimulus and then a half hour with the other, this negative transfer was not obtained.[23] It appears that exposure of the two stimuli in rapid alternation causes the two different stimuli to be classed within the same concept representative. This makes it very difficult for the bird to distinguish between them later as separate concepts in a choice learning task. From a functional point of view, exposure to stimuli in rapid succession is similar to obtaining different views of the parent, as both the parent and the baby move about and change their relative positions to each other. It would be highly functional if these different views of the same object were put together into a single integrated concept, but in this artificial task it was dysfunctional.

Long-term Consequences

The most immediate long-term consequence of imprinting is to determine the particular object that the young bird will approach, follow, and want to be near. This permits the young bird to distinguish its own parent from the parents of other organisms. Although the evidence is somewhat less definitive, on a longer-term basis it appears that even adult social and sexual preferences are strongly influenced by the nature of the initial imprinting object. It is also of some importance that the imprinting object can later be used as reinforcement for the learning of other responses such as pecking. That is to say, a young bird will learn a pecking response if it is reinforced by presentation of the imprinting object. Thus, specific objects acquire reinforcement properties as a result of imprinting.

Other Possible Examples of Imprinting

A variety of other learning processes have been alleged to involve imprinting to some degree, but the absence of sharply defined critical periods has made it extremely difficult to distinguish these from the development of attachments via extrinsic reinforcement. Among the processes that certain investigators think may involve imprinting are all attachments of young to parents, including the attachments of monkeys to nonliving surrogate mothers.[24] (In the absence of their real mothers, young monkeys develop strong attachments to soft objects and spend a great deal of time clinging to them, running to them when they become frightened, etc.) The attachments of human infants to parents, and of the parents to their young, might also involve imprinting to some degree.

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[22] P. P. G. Bateson, "Internal Influence on Early Learning in Birds," in Hinde and Stevenson-Hinde, *Constraints on Learning*, pp. 112-13.

[23] Bateson, "Internal Influence."

Some investigators believe that certain organisms develop various forms of locality imprinting. For example, the digger wasp learns its home burrow nest. Migrating fish such as the salmon learn the characteristic odor of the stream in which they were born.[25] Some migrating birds learn the visual pattern characteristics of certain constellations via some special learning process that might be similar to imprinting.[26] It has been suggested that some insects may develop food imprinting to the particular type of leaf they feed upon.[27]

PREPARED SENSORY-MOTOR LEARNING

A number of years ago it was discovered by accident that infant rats require some initial tactile stimulus to the genital region to initiate the urination reflex. Without this environmental "trigger," the reflex does not function and the baby rats die of ruptured bladders. The reflex connection from the stimuli associated with bladder distension to the urination response is genetically established, and, so far as is known, there are no options in the nature of this connection. Nevertheless, experience does play a vital role in the initial "toning up" of this reflex.[28]

Another case where the sensory-motor connections are almost completely specified genetically but experience tones up the accuracy or precision of the connections is in the acquisition of visually guided pecking in newly hatched chicks. Baby chicks have an innate tendency to peck at small objects, with initial pecking being centered on the goal object, but there is considerable scatter in their initial visually guided pecking. Pecking accuracy improves with practice, but it also improves simply with age, when the

[24] H. F. Harlow, M. K. Harlow, and S. J. Suomi, "From Thought to Therapy: Lessons from a Primate Laboratory." *American Scientist,* 1971 (59), 538-49.

[25] Thorpe, *Learning and Instinct,* p. 305.

[26] S. T. Emlen, "Celestial Rotation: Its Importance in the Development of Migratory Orientation." *Science,* 1970 (170), 1198-1201.

[27] Thorpe, *Learning and Instinct,* pp. 286-89.

[28] A. Manning, "The Development of Behavior," in Seligman and Hager, *Biological Boundaries,* pp. 260-77.

chicks are reared either in the dark or with visual occluders over the eyes to prevent pattern vision. Thus, the improvement in pecking accuracy occurs both as a function of purely maturational changes in the chick and as a function of specific experience in visually guided pecking.[29]

The range of potential interaction between genetics and learning is perhaps best demonstrated in the acquisition of bird song.[30] At one extreme, completely isolated male song sparrows can develop normal song despite the fact that their song is more complex than that of many species that require exposure to the song of their species during development. Somewhat less rigid genetic determination of song is exhibited by juncos, which develop abnormal song reared in isolation, but can develop quite normal song when raised with a group of other vocally inexperienced young juncos. It is a successful case of "the blind leading the blind," perhaps because each young junco possesses some component of the normal song, which is different for different juncos. This, in combination with the genetic predisposition to learn the normal song, leads to normal song development among young juncos raised in a group.

Experience plays a greater role in relation to inheritance in the acquisition of song by white-crowned sparrows. White-crowned sparrows exhibit local song dialects—that is, the singing characteristic of sparrows living in one region differs somewhat from the singing of white-crowned sparrows that live in another region. Reared in isolation, however, white-crowned sparrows from different regions develop the same simplified version of the normal song. Clearly they acquire the local dialect by listening to adult birds. Controlled experiments demonstrate that there is a critical period up to about three or four months of age during which isolated males can be trained to sing whatever dialect of their species song they are exposed to. Beyond four months of age, there is no capability to acquire song by such training. This is particularly interesting because young white-crowned sparrows do not actually begin to produce the song themselves until several months after the end of the critical period for exposure to adult song. The young birds must be forming a sensory memory trace for the song dialect that subsequently guides the acquisition of their own song.

This acquisition of song has been shown to depend upon comparison of produced song with sensory feedback from auditory receptors. Young birds deafened after the critical period but before they begin to produce song can't acquire the song they had been previously exposed to. The young bird has to be able to hear itself sing and compare its song to the previously acquired memory trace for adult song in order to develop adult song with the appropriate dialect.

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[29] W. W. Cruze, "Maturation and Learning in Chicks." *Journal of Comparative Psychology,* 1935 (19), 371-409.

[30] All the material in this section on bird songs was obtained from P. Marler, "A Comparative Approach to Vocal Learning: Song Development in White-Crowned Sparrows." *Journal of Comparative and Physiological Psychology,* 1970 (71), 1-25.

Another genetic constraint on the acquisition process is that exposure to the song of another species is almost completely ineffective in influencing the song development of white-crowned sparrows, whether they are exposed to the alien song in combination with normal song or in isolation. There is a strong genetic predisposition to learn a dialect within the range of white-crowned sparrow songs and not outside that range.

PREPAREDNESS AND CONDITIONING

Generality of Conditioning

Studies of classical and instrumental conditioning have tended to concentrate on relatively arbitrary pairings of stimuli and responses. Of course, the organism must be sensitive to the *CS*, and the *CR* must be within its potential behavioral repertoire, but pure tones, bar presses, and the like are not likely to be a significant part of the natural experience of most lower organisms. More importantly, pairings between stimuli and responses are largely arbitrary and at best only analogous to naturally occurring contingencies. The fact that successful instrumental and classical conditioning has been demonstrated with a large variety of arbitrarily related stimulus-response (*SR*) pairs has led many to believe in what might be called the *generality principle of conditioning*, which is that for organisms capable of conditioning, any stimulus can be conditioned to any response. An even more extreme statement of such a position is that any response can be associated to any stimulus with equal ease.

Stated in the extreme form, the generality principle is clearly false. There are enormous differences in the ease of conditioning different stimuli and responses in the same organism, and there are also a small but significant number of known failures to condition. Breland and Breland conditioned a huge variety of unusual behaviors in 38 species totalling more than 6000 animals over a period of many years, but they report a number of consistent failures of animals to learn particular behaviors.[31] In many instances the animal began to perform the appropriate conditioned behavior only to exhibit a complete disintegration of performance because of the substitution of behavior that appeared to be part of the innate repertoire of the organism. For example, pigs trained to deposit large wooden coins in a "piggy bank" to get reinforcement began to perform the conditioned response, but their performances progressively deteriorated because they would repeatedly drop the coin, root it, drop it again, toss it

[31] K. Breland and M. Breland, "The Misbehavior of Organisms." *American Psychology*, 1961 (61), 681-84.

up in the air, and so forth. This rooting behavior is, of course, a strongly established natural response pattern connected with food, and for some reason, this response was so dominant in the situation that a new, more arbitrary, response could not be learned and maintained at any high criterion.

Laboratory experiments have demonstrated that certain simple reflexes are very difficult to condition, and that instrumental conditioning of autonomic responses is also somewhat difficult to obtain. Hence it does not appear that all stimuli are equally associable to all responses. The innate or learned *preparedness* or *contrapreparedness* of the organism to learn a particular association must be taken into account.[32]

From the standpoint of preparedness, there is probably no sharp break between some highly prepared single-contingency forms of learning, such as sensitization, habituation, imprinting, or song learning in birds and highly prepared multiple-contingency conditioning. These various forms can be considered on a continuum of variety of possibilities for strengthening or weakening different associations.

The most highly prepared form of learning, short of complete innate specification, is that which occurs when a stimulus is innately connected to a particular response but experience determines the strength of that connection. An example of this is the triggering of the urination reflex mentioned earlier. Imprinting is somewhat less highly prepared in that a variety of potential stimuli can be associated to a particular response pattern (following and attraction). The sensory and motor sequence learning that occurs when birds acquire song exhibits a variety of degrees of preparedness for different species, with some species having a very narrowly specified range of learnable songs and other species having a broader range.

Preparedness is present in all forms of learning, and is an important concept in the analysis of conditioning as well. An attractive generalization suggested by consideration of the role of preparedness in learning is that an important part of the phylogenetic and ontogenetic development of learning is the increasing capacity for associative generality—that is, an increasing ability to associate anything with anything else with close to equal ease. In many ways, the cerebral cortex appears to be organized in such a way as to provide a close approximation to complete associative generality, such that the larger the cortex of an organism, the greater the degree of associative generality. According to this notion, subcortical conditioning is much more constrained and influenced to a greater extent by the relative degrees of preparedness or contrapreparedness. The same sort of preparedness may also be an important dimension in understanding the development of learning capacity, with young organisms exhibiting more highly prepared learning and less associative generality than adult organisms.

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[32] M. E. P. Seligman, "On the Generality of the Laws of Learning." *Psychological Review*, 1970 (77), 406-18. See also Seligman and Hager, *Biological Boundaries*.

Autoshaping

Although most experimentally conditioned responses are relatively unnatural in relation to the stimuli or the reinforcements employed, the key pecking that pigeons do to obtain food in a Skinner box is closely related to the way pigeons ordinarily obtain food, namely, by pecking. Hence, pecking for food might be considered a highly prepared association that would be learned rather easily. This is true, and, in fact, the association is so easily learned that a rather amazing phenomenon known as autoshaping has been demonstrated by Brown and Jenkins and others for pigeons' key pecking.[33]

The autoshaping paradigm is a classical conditioning procedure of pairing the illumination of a key with the delivery of food. The experimenter lights the key just before delivering food to the pigeon. This is a *CS-US* pairing that is in no way dependent on the pigeon's behavior. In particular, pecking the key after the light comes on does not affect the probability or latency of food delivery. Nevertheless, under these conditions pigeons start pecking the key and increase their rate of pecking to a very high rate. The pecking elicited by the food, the *US*, comes to be elicited by the *CS*, the light. Such autoshaping occurs even though the pecking has no effect on the probability of food reinforcement. Thus, a classical conditioning procedure is being used.

More amazing is that the *CR*—the key peck—occurs even when the pecks turn off the key and prevent the delivery of food reinforcement.[34] Furthermore, autoshaping can be demonstrated when the key is at a substantial distance from the food-dispensing mechanism. Thus, a highly prepared conditioned response can be acquired under conditions where it is very dysfunctional for the organism and where most other associations would not be learned or maintained.

Learned Food Aversion

The most widely studied example of highly prepared learning is the association of tastes with subsequent illness. Martin Seligman has provided us with an interesting personal anecdote, which he has labeled the *sauce Bearnaise phenomenon,* that illustrates some important aspects of learned taste aversions.[35] Some years ago he came down with stomach flu about six hours after eating filet mignon with sauce Bearnaise. This association of the taste and illness caused him to develop a strong dislike for sauce Bearnaise, though he did not develop a dislike for steak, the plates from which he ate the sauce, the opera he heard in the interim, the people he associated with during that time, or anything else associated with the experience—just the sauce Bearnaise. A very long time, six hours, intervened between experiencing the visual and taste *CS*s and the *US*, the resulting illness. Finally he determined definitely that a virus had caused his illness, not the sauce Bearnaise; nevertheless he could not rid himself of this strong taste aversion. Sauce Bearnaise, once his favorite sauce, still tastes awful to him.

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[33] P. L. Brown and H. M. Jenkins, "Auto-Shaping of the Pigeon's Key Peck." *Journal of Experimental Analysis of Behavior*, 1968 (11), 1-8. B. R. Moore, "The Role of Directed Pavlovian Reactions in Simple Instrumental Learning in the Pigeon," in Hinde and Stevenson-Hinde, *Constraints on Learning*, pp. 159-88. H. M. Jenkins, "Effects of the Stimulus-Reinforcer Relation on Selected and Unselected Responses," in Hinde and Stevenson-Hinde, *Constraints on Learning*, pp. 189-206.

[34] D. R. Williams and H. Williams, "Auto-Maintenance in the Pigeon: Sustained Pecking Despite Contingent Non-Reinforcement." *Journal of the Experimental Analysis of Behavior*, 1969 (12), 511-20.

Seligman has been one of the primary advocates of the importance of considering preparedness as a dimension of conditioning, and the phenomena he cites to differentiate highly prepared from less prepared associations are extremely convincing on this matter.[36]

Perhaps the best experimental demonstration of the importance of preparedness for learning different associations was provided in an experiment by Garcia and Koelling.[37] They employed two conditioned stimuli, taste and an audiovisual stimulus, which were both paired with subsequently induced radiation sickness. Under these conditions, only the taste, not the audiovisual stimulus, became aversive. However, when another group of rats was given the same two *CS*s paired with foot shock, the audiovisual stimulus became aversive and not the taste. Rats are highly prepared to associate tastes with illness despite *CS-US* interval on the order of hours, but they are contraprepared to associate various audiovisual signals with illness. They are also highly prepared to associate audiovisual signals with various kinds of externally administered pain, while they are contraprepared to associate taste with such pain.[38]

Organisms can learn that a food is safe to eat. Revusky and Bedarf have demonstrated that when an organism eats several foods and later becomes ill, it is the most novel foods that become aversive.[39] When there is a relatively novel food, to which to attach the aversion, little or no aversion is developed for foods that have been consumed frequently in the past without unpleasant consequences. Even when only a single type of food is consumed, the more often the organism has eaten it without adverse consequences, the less aversion is developed from a later pairing of the food with subsequent illness.[40] Rozin and Kalat term this effect *learned safety*.

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[35] Seligman and Hager, *Biological Boundaries,* pp. 8-9.

[36] Seligman, "On the Laws of Learning."

[37] J. Garcia and R. A. Koelling, "Relation of Cue to Consequence in Avoidance Learning." *Psychonomic Science,* 1966 (4), 123-24.

[38] J. Garcia, F. R. Ervin, and R. A. Koelling, "Learning with Prolonged Delay of Reinforcement." *Psychonomic Science,* 1966 (5), 121-22. J. C. Smith and D. L. Roll, "Trace Conditioning with X-Rays as the Aversive Stimulus." *Psychonomic Science,* 1967 (9), 11-12. S. H. Revusky, "Aversion to Sucrose Produced by Contingent X-Irradiation—Temporal and Dosage Parameters." *Journal of Comparative and Physiological Psychology,* 1968 (65), 17-22.

[39] S. H. Revusky, and E. W. Bedarf, "Association of Illness with Prior Ingestion of Novel Food." *Science,* 1967 (155), 219-20.

Taste aversions can be formed even with *CS-US* intervals of several hours, but the effectiveness of the conditioning begins to decrease with increasing delay.[41] Thus, there is no reason to believe that the *law* regarding the importance of contiguity for the formation of associations is different as a function of preparedness, but there is a considerable difference in the rate parameter. The highly prepared character of learned taste aversions—namely that only stimuli closely associated with food consumption become aversive—may provide the functional explanation for the ability to tolerate long *CS-US* intervals. Associating everything that occurs within a six-hour period one to another would normally be very dysfunctional, so the rate parameter must be such as to produce a substantial decline in conditionability with increasing *CS-US* interval. But since learned taste aversion is so highly prepared that only stimuli associated with food (generally a novel food at that) can be conditioned, and then only to illness-induced aversion, there is relatively little opportunity for dysfunctional taste aversion learning (Seligman's experience with sauce Bearnaise being one counterexample). Along the same line, there have been observations of the natural behavior of animals given a choice of more than one new food. Under such conditions animals tend to eat one new food at a time, minimizing the chance of developing incorrect food aversions.[42]

The mechanism of learned safety may also account for a portion of the eventual decline in conditioned aversiveness of a food with increased delay between consumption and illness. As time elapses since consumption, the animal is learning that the food is safe, and this interferes with learning that it is aversive. Nachman and Jones demonstrated that not all the delay gradient can be explained by learned safety, since even a highly familiar food will acquire some aversiveness if paired with illness, and such conditioning shows a pronounced delay gradient.[43]

The subcortical character of taste aversion learning has been suggested by experiments showing: (1) that taste aversions can be learned even under deep anesthesia,[44] and (2) that such learned taste aversions survive the effects of electroconvulsive shock and cortical spreading depression delivered shortly after the organism consumes the food.[45] Such procedures block the formation of more cognitive learning and conditioning.

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[40] J. W. Kalat and P. Rozin, " 'Learned Safety' as a Mechanism in Long-Delay Taste-Aversion Learning in Rats." *Journal of Comparative and Physiological Psychology*, 1973 (83), 198-207.

[41] Smith and Roll, "Trace Conditioning with X-Rays."

[42] P. Rozin, "Adaptive Food Sampling Patterns in Vitamin-Deficient Rats." *Journal of Comparative and Physiological Psychology*, 1969 (69), 126-32. P. Rozin and J. W. Kalat, "Learning as a Situation-Specific Adaptation," in Seligman and Hager, *Biological Boundaries*, pp. 66-96.

[43] M. Nachman and D. R. Jones, "Learned Taste Aversions over Long Delays in Rats: The Role of Learned Safety." *Journal of Comparative and Physiological Psychology*, 1974 (86), 949-56.

Finally, there are species differences in learned food aversion. For example, Japanese quail appear to be more prepared to associate the visual characteristics of food rather than its taste with subsequent illness.[46]

The study of learned food aversions has already suggested some potential practical applications. Gustavson, Garcia, Hankins, and Rusiniak demonstrated that making coyotes sick by feeding them poisoned lamb's meat can, in one or two treatments, suppress their tendency to attack lambs.[47] This opens up the possibility of reducing coyote attacks on sheep by means other than massive killing of coyotes. In aversion therapy for behavior modification of alcoholics, Wilson and Davison suggest that it may be more effective to use illness as an aversive consequence of alcohol consumption than, say, electric shock.[48]

Learned Food Preferences (Specific Hungers)

Work on preparedness in learned food aversion provided the solution to the moderately longstanding problem of how organisms learn the substances to eat in order to get adequate nutrition. For a number of years there had been experiments demonstrating that animals deficient in a nutrient (such as thiamine or riboflavin) would consume foods containing that nutrient in preference to foods that did not. It seemed difficult to believe that organisms were equipped with specific detectors for each needed nutrient and that nutrient-specific drive centers made the taste of substances containing that nutrient more desirable. The work on learned food aversions led Paul Rozin and his colleagues to suggest the elegant hypothesis that new diets are sought out because the old diet, which is deficient in some nutrient, has become aversive owing to its association with the illness produced by the dietary deficiency.[49]

[44] D. L. Roll and J. C. Smith, "Conditioned Taste Aversion in Anesthetized Rats," in Seligman and Hager, *Biological Boundaries,* pp. 98-102.

[45] M. Nachman, "Limited Effects of Electroconvulsive Shock on Memory of Taste Stimulation." *Journal of Comparative and Physiological Psychology,* 1970 (73), 31-37. P. Best and K. Zuckerman, "Subcortical Mediation of Learned Taste Aversion." *Physiology and Behavior,* 1971 (7), 317-20.

[46] H. C. Wilcoxon, W. B. Dragoin, and P. A. Kral, "Illness-Induced Aversions in Rat and Quail: Relative Salience of Visual and Gustatory Cues." *Science,* 1971 (171), 826-28.

[47] C. R. Gustavson, J. Garcia, W. G. Hankins, and K. W. Rusiniak, "Coyote Predation Control by Aversive Conditioning." *Science,* 1974 (184), 581-83.

[48] G. T. Wilson and G. C. Davison, "Aversion Techniques in Behavior Therapy." *Journal of Consulting and Clinical Psychology,* 1968 (33), 327-29.

[49] P. Rozin, "Specific Aversions as a Component of Specific Hungers." *Journal of Comparative*

There is now considerable evidence in favor of this hypothesis, beyond its elegance and parsimony by comparison to the hypothesis of specific hungers. For example, when a nutrient deficiency develops, rats demonstrate a strong aversion to their familiar (deficient) diet. They don't eat it, they spill it and redirect their feeding responses, even to the extent of chewing inedible objects when no alternative food is available. And when an alternative food is available, they prefer it. They also prefer a familiar food that they do not associate with deficiency-induced illness to a completely novel food.[50] Novel foods are only preferred to familiar aversive foods. If the new diet does not lead to recovery, the animals will continue to seek out and eat new foods until they find one that makes them feel better. Once such a food has been discovered, they stick with that food and show no interest in trying out other novel foods.

Rats also appear to learn specific food preferences as well as aversions and safety. They come to prefer foods associated with recovery from illness,[51] just as they avoid foods associated with the onset of illness. The same principles appear to apply to both learned food preferences and learned food aversions, though aversions appear to develop much more strongly and rapidly than safety and preferences. This would appear to be adaptive.

SUMMARY

1. Sensitization is the enhanced tendency of an organism to emit some response (typically arousal, orienting, or withdrawal) to a mild warning signal as a consequence of the (repeated) occurrence of strong warning or aversive stimuli.
2. Habituation is the reduced tendency of an organism to emit some response (typically arousal, orienting, or withdrawal) to a mild warning stimulus as a consequence of the (repeated) occurrence of the mild warning stimulus.
3. Sensitization and habituation are single-contingency forms of learning

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and Physiological Psychology, 1967 (64), 237-42. P. Rozin and J. W. Kalat, "Specific Hungers and Poison Avoidance as Adaptive Specializations of Learning." *Psychological Review*, 1971 (78), 459-86.

[50] P. Rozin, "Specific Aversions and Neophobia as a Consequence of Vitamin Deficiency and/or Poisoning in Half-Wild and Domestic Rats." *Journal of Comparative and Physiological Psychology*, 1968 (66), 82-88.

[51] J. Garcia, F. R. Ervin, C. H. Yorke, and R. A. Koelling, "Conditioning with Delayed Vitamin Injection." *Science*, 1967 (155), 716-18. D. M. Zahorik and S. F. Maier, "Appetitive Conditioning with Recovery from Thiamind Deficiency as the Unconditioned Stimulus." *Psychonomic Science*, 1969 (17), 309-10.

that are fundamentally linked in that sensitization counteracts the effects of habituation (produces dishabituation).

4. Habituation to a repeated stimulus and sensory adaptation are both single-contingency forms of learning, but they differ in several important respects. Sensory adaptation is a nonassociative memory change in the sensitivity of peripheral sensory receptors that affects the likelihood of eliciting all the responses connected to those sensory cells. Habituation is probably an associative memory change in the connection from a stimulus node to a particular response pattern. Sensory adaptation decreases sensitivity to a wide variety of stimuli, while habituation is confined to a small class of highly similar stimuli. Habituation can be reversed (dishabituation) by presentation of a novel sensitizing stimulus, while adaptation cannot be. Finally, their storage and acquisition dynamics are also different. The effects of habituation can last much longer than the effects of adaptation (weeks versus tens of minutes). Habituation is very effective with long delays between repetitions of a stimulus, while adaptation is sharply reduced by such spacing.
5. Exposure of a young duckling, gosling, or chick to a model during the critical period (which begins about five hours after hatching) causes the young bird to treat the model as its parent. This type of learning is called imprinting. Imprinting is faster for models that are similar to adult members of the species. Within the critical period, more preferred models will be selected for imprinting over less preferred models. The critical period appears to end when the young bird has become strongly imprinted on some model, and thereafter it is impossible to reverse the attachment by exposure to a more suitable model.
6. Many birds require exposure to a dialect of the song of their species during a critical period in order to learn, sometimes several months later, to produce that song.
7. Sensitization, habituation, imprinting, and song learning in birds are examples of highly prepared, single-contingency learning in that only very specific *S-R* connections can be strengthened or weakened by the (repeated) exposure to specific types of stimuli.
8. Multiple-contingency classical and instrumental conditioning also exhibit vast differences in degree of preparedness. Organisms are highly prepared to learn some associations and not prepared or even contraprepared to learn other associations. For example, we are prepared to associate tastes with subsequent illness and contraprepared to associate transient environmental stimuli (such as lights and sounds) with illness. However, cognitive learning in human beings does appear to possess a considerable degree of associative generality, that is, an approximately equal ease of learning a wide variety of different associations.

9. Strong aversions to a food develop when consumption of the food is followed by illness, even when hours elapse between eating and illness. Specific food preferences can also be learned when consumption of these foods is associated with recovery from illness. Novel foods are much more likely to become aversive owing to association with subsequent illness than familiar foods that have frequently been consumed in the past without unpleasant aftereffects. Organisms can learn that a food is safe.

3 Classical Conditioning

OBJECTIVES

1. To describe the experimental procedures of classical conditioning.
2. To present the basic facts of acquisition and extinction in classical conditioning as a function of various conditions.
3. To discuss the concept of inhibition and to describe the role it may play in discrimination, generalization, the timing of the conditioned response, and elimination of the conditioned response in extinction.
4. To discuss the relationship between conditioned and unconditional responses.
5. To discuss what is learned in elementary classical conditioning and in more complex paradigms such as higher-order conditioning, sensory preconditioning, conditioned inhibition, and configuring.
6. To discuss the role of stimulus salience and selective attention in classical conditioning.
7. To describe the configuring phenomenon found for higher species and to point out the probable dependence of configuring upon the capacity for chunking.

You are watching television late one evening and you see someone frying bacon and eggs over an open campfire. Suddenly you begin to feel hungry, and you may even salivate a little. You get up, go to the refrigerator, and fix yourself something to eat. Such a hunger reaction to visual and auditory stimuli connected with food is an example of classical conditioning. Certain tastes and smells may or may not be innately associated to feelings of hunger, but hunger reactions to sights and sounds connected with satisfactory food must surely be learned by pairing such sights and sounds with good tastes and smells and ultimately with satisfying one's hunger.

Consider an example of aversive conditioning. You hear a bee buzzing or see a snake or a spider, and perhaps you become mildly anxious or even deathly afraid. Such reactions are almost certainly not innate, though it may be hard to pinpoint the precise learning experiences in your childhood that produced the association between such stimuli and fear reactions. Perhaps you were stung or bitten, but as likely as not the conditioning was a result of a fear reaction of your parents, siblings, or friends.

Are you afraid of the dark? If you had the kind of older brother or sister that I was, you have a good reason. When I was a little boy, I used to hide behind a door or in a dark room or hallway and jump out at my younger brothers to scare them. I do not know how much fear *they* developed of the dark, but by some sort of divine justice I made *myself* afraid of the dark (which I distinctly remember I had not been before), and I only gradually lost it over a period of many years. Of course, there may be some degree of innate fear of the dark, and conceivably of snakes, spiders, and bees as well, but the magnitude of these fears is very definitely subject to learning.

Such learning is probably classical conditioning, and it is a true example of associative learning because it depends on the pairing of two or more events. The sight of food (conditioned stimulus, *CS*) is associated with hunger reactions (conditioned response, *CR*) by pairing the *CS* with an unconditioned stimulus (*US*) consisting of the taste of food in the mouth or other stimuli associated with food consumption. The emotional and behavioral components of a fear reaction (*CR*) may be associated with a *CS* by virtue of the pairing of the *CS* with pain or a danger (*US*).

ACQUISITION: CONCEPTS AND PARADIGMS

The first systematic experimental studies of the process by which organisms learn the association between two paired stimuli were performed by the Russian physiologist Pavlov (though an American chauvinist could make some claim on behalf of Twitmeyer).[1] Pavlov's classical conditioning experiments were concerned with conditioning the secretory response of salivation in dogs. In order to measure the magnitude of the salivary response, dogs were first subjected to an operation in which the duct of a salivary gland was diverted into a tube inserted through the cheek. Then they were trained to stand quietly in a harness on a table in an acoustically insulated room (to prevent uncontrolled distraction by noise). The training trials in the classical conditioning paradigm involved presentation of a stimulus such as a tone followed a few seconds later by presentation of a dish of meat for the dog to eat. The strength of association between the *CR* and the *CS* alone was determined periodically by test trials in which the tone was presented alone for 30 seconds and the amount of salivation was measured.

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[1] I. P. Pavlov, *Conditioned Reflexes: An Investigation of the Physiological Activity of the Cerebral Cortex* (1927). Trans. G. V. Anrep. New York: Dover, 1960. E. B. Twitmeyer, "A Study of the Knee-Jerk" (unpublished doctoral dissertation, University of Pennsylvania, 1902). See *Journal of Experimental Psychology*, 1974 (103), 1047-66.

Before the tone *CS* and the food *US* were paired, the food produced a salivary *UR*, but the tone produced no salivation. The tone did produce an orienting response, which indicated that the dog was paying attention to the stimulus, but such orienting responses habituate upon repeated presentation of the stimulus, provided the stimulus is not associated with the occurrence of any other significant event. When the tone regularly preceded the food, after perhaps 20 trials a substantial amount of salivation was elicited by the tone *CS*. Furthermore, over successive conditioning trials, the amount of salivation progressively increased. Also, when the conditioned salivary response occurred, it typically began as much as 20 seconds following the onset of the tone, but later it often began only one or two seconds following *CS* onset. It is evident from this that we can use various response measures to indicate an increase in the strength of conditioning with repeated trials: the probability of occurrence of any salivation above baseline level, the magnitude of the salivation, and the decrease in latency of salivation.

Conditioned salivation is an example of *appetitive* classical conditioning, since food is a positive stimulus and the *CS* comes to be associated with the occurrence of such a positive stimulus. Classical conditioning can also be based on an *aversive US*, such as electric shock. A common example of aversive classical conditioning, one with a skeletal rather than a glandular response, consists of the pairing of a *CS* such as a light or tone with a *US* consisting of a shock to one of the legs of an animal.[2] Shock to the leg produces a leg flexion withdrawal response as well as changes in the autonomic responses such as heart rate, galvanic skin response (GSR), and other indicants of arousal or fear. Repeated pairing of the *CS* and *US* leads to flexion and autonomic responses to the *CS* alone, though in this case extended conditioning will often increase the latency of the flexion *CR* so that it occurs just prior to the expected shock.

A conditioned emotional response (*CER*) such as fear can also be measured indirectly by its interference with some other ongoing behavior. For example, if a tone has been paired with shock, the degree to which an animal has developed a conditioned fear response to the tone can be measured by presenting the tone when the animal is thirsty and licking water from a drinking tube. Such a tone will interrupt drinking and slow down the rate of licking. The magnitude of this effect provides an indirect measure of the strength of association between the tone and the conditioned fear response.

The first experiment that indirectly assessed the strength of classical conditioning of a stimulus to fear through its depression of ongoing behavior was performed by Estes and Skinner.[3] Rats were taught to press a lever at a certain rate in order to receive a pellet of food periodically. The training procedure was a four-minute *fixed-interval schedule* of reinforcement, in that the rats received a food pellet for the first response after each four-minute interval. After two weeks of daily one-hour training sessions the rats were lever pressing at a moderately high and reasonably consistent overall rate (ignoring cyclical fluctuations). Then for the next six sessions the rats received three-minute auditory stimuli terminated by electric shock. The increasing strength of association between the auditory stimulus and the shock was measured by the decreasing rate of bar pressing during presentation of the auditory (warning) stimulus. Figure 3-1 presents a simplified illustration of response suppression.

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[2] H. S. Liddell, "The Conditioned Reflex," in F. A. Moss (ed.), *Comparative Psychology*. Englewood Cliffs: Prentice-Hall, 1934.

Another well-known classical conditioning paradigm is the conditioned eyeblink. A *CS* such as a tone is paired with a small puff of air delivered to the eyeball (*US*), which elicits an unconditioned eyeblink response. After several pairings of the *CS* and *US*, the *CS* by itself will elicit a conditioned eyeblink.

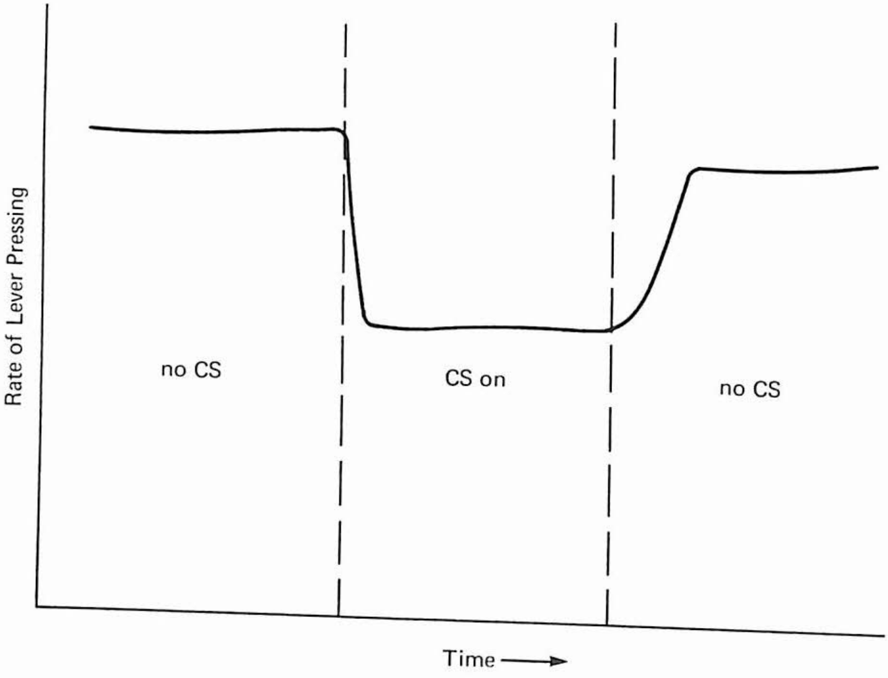

Figure 3-1. Idealized diagram showing suppression of a *CR* (lever pressing) during presentation of a fear inducing *CS*.

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[3] W. K. Estes and B. F. Skinner, "Some Quantitative Properties of Anxiety." *Journal of Experimental Psychology*, 1941 (29), 390-400.

Speaking functionally, classical conditioning serves to allow an organism to anticipate a future event and thereby make appropriate emotional and skeletal behavioral responses in anticipation of that event. It does not permit an organism to change the events that occur in the world, but it probably does change the effects these events have on the organism. Like the single-contingency forms of learning discussed in Chapter 2, classical conditioning permits the organism to adapt to the world as it exists, not to change it.

EXTINCTION

Classically conditioned responses can be eliminated by a procedure known as *extinction*. Extinction is the repeated presentation of the *CS* not followed by the *US*. Extinction gradually reduces the probability of the *CR* in response to the *CS*. Note that unpaired presentation of the *CS* by itself is formally analogous to a habituation procedure. The difference is that extinction is the weakening of a previously established conditioned response, whereas habituation is the weakening of (presumably) unlearned, innate responses to a stimulus.

Extinction is but one of many ways to decrease performance of a *CR* to a *CS*. It should be distinguished from decay, which is a decrement due to the passage of time alone, independent of experience. The speed of extinction is many orders of magnitude greater than the speed of ordinary forgetting in the case of classically conditioned responses. Under some conditions, extinction can be about 90 percent complete after ten to fifteen extinction trials distributed over a period of less than five minutes.[4] The rate of forgetting of classically conditioned responses is much slower—some studies yield substantial retention after months and even years.[5] Extinction is also experimentally distinguishable from *counterconditioning*, in which a *CS* is associated with a different *CR*, which may result in interference between the two *CR*s. The greater the incompatibility of the two *CR*s, the greater the interference.

The *CS* is not the only stimulus present in a classical conditioning experiment; there are background context (situational) cues as well. There is evidence that some of these context cues become associated with the *CS* and play a role in maintaining the *CR* during extinction. Presentation of the *US* from time to time during extinction will retard extinction in particular, even though it is not paired with the *CS*.[6] As Capaldi and Mackintosh have suggested, the ideal conditions for investigating extinction of a specific *CS-US* association might be provided by simply removing the *CS-US* pairing, and continuing to present both *CS* and *US* at the same rate as during acquisition but in an unpaired (or random noncontingent) manner.[7]

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[4] J. W. Kling, "Learning: Introductory Survey," in J. W. Kling and L. A. Riggs, *Experimental Psychology*, Vol. 2. New York: Holt, Rinehart and Winston, 1971, p. 570.

[5] G. A. Kimble, p. 281. *Hilgard and Marguis' Conditioning and Learning*. Englewood Cliffs: Prentice-Hall, 1961, p. 281. Also N. J. Mackintosh, *The Psychology of Animal Learning*. New York: Academic Press, 1974, pp. 472-75.

SPONTANEOUS RECOVERY

Extinction is not the simple reversal of prior conditioning. One source of evidence that this is so the phenomenon of *spontaneous recovery* from extinction. In his salivary conditioning experiments, Pavlov demonstrated extinction by presenting the auditory *CS* not followed by the food. After a few trials the conditioned salivary response extinguished. However, after the end of the formal extinction trials in a session, a rest period of as little as 20 minutes was enough to restore the salivary response to the tone to a considerable extent.[8] The longer the delay following extinction, the greater the amount of spontaneous recovery, up to a maximum after a day's rest of perhaps 50 percent of the response strength lost during the extinction trials in the previous session.[9]

A series of spaced extinction sessions will produce a decrement in the *CR* during the extinction trials within a session, followed by spontaneous recovery of a portion of the lost response strength between sessions, followed by continued extinction and spontaneous recovery, until extinction is complete and the degree of spontaneous recovery between sessions negligible. A hypothetical example of this process is shown in Figure 3-2.

Over the delay between acquisition sessions, there is no significant change in the probability of performance of the *CR*, while there is substantial spontaneous recovery between sessions in extinction. Thus it is clear that extinction from the 90 percent to the 50 percent level of performance of the *CR* could not be producing a memory trace equivalent to that produced by original acquisition to the 50 percent level. Extinction is not the simple reversal of acquisition. Acquisition plus some extinction produces more or different memory traces from that produced by less acquisition alone, even when equated for level of performance of the *CR*. Further

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[6] K. W. Spence, "Cognitive and Drive Factors in the Extinction of the Conditioned Eye-blink in Human Subjects." *Psychological Bulletin*, 1966 (73), 445-58. J. J. B. Ayres and M. J. DeCosta, "The Truly Random Control as an Extinction Procedure." *Psychonomic Science*, 1971 (24), 31-33.

[7] E. J. Capaldi, "A Sequential Hypothesis of Instrumental Learning," in K. W. Spence and J. T. Spence (eds.), *The Psychology of Learning and Motivation*, Vol. 1. New York: Academic Press, 1967, pp. 67-156. Mackintosh, *The Psychology of Animal Learning*, pp. 433-34.

[8] Pavlov, *Conditioned Reflexes*.

[9] Kimble, *Conditioning and Learning*, p. 284.

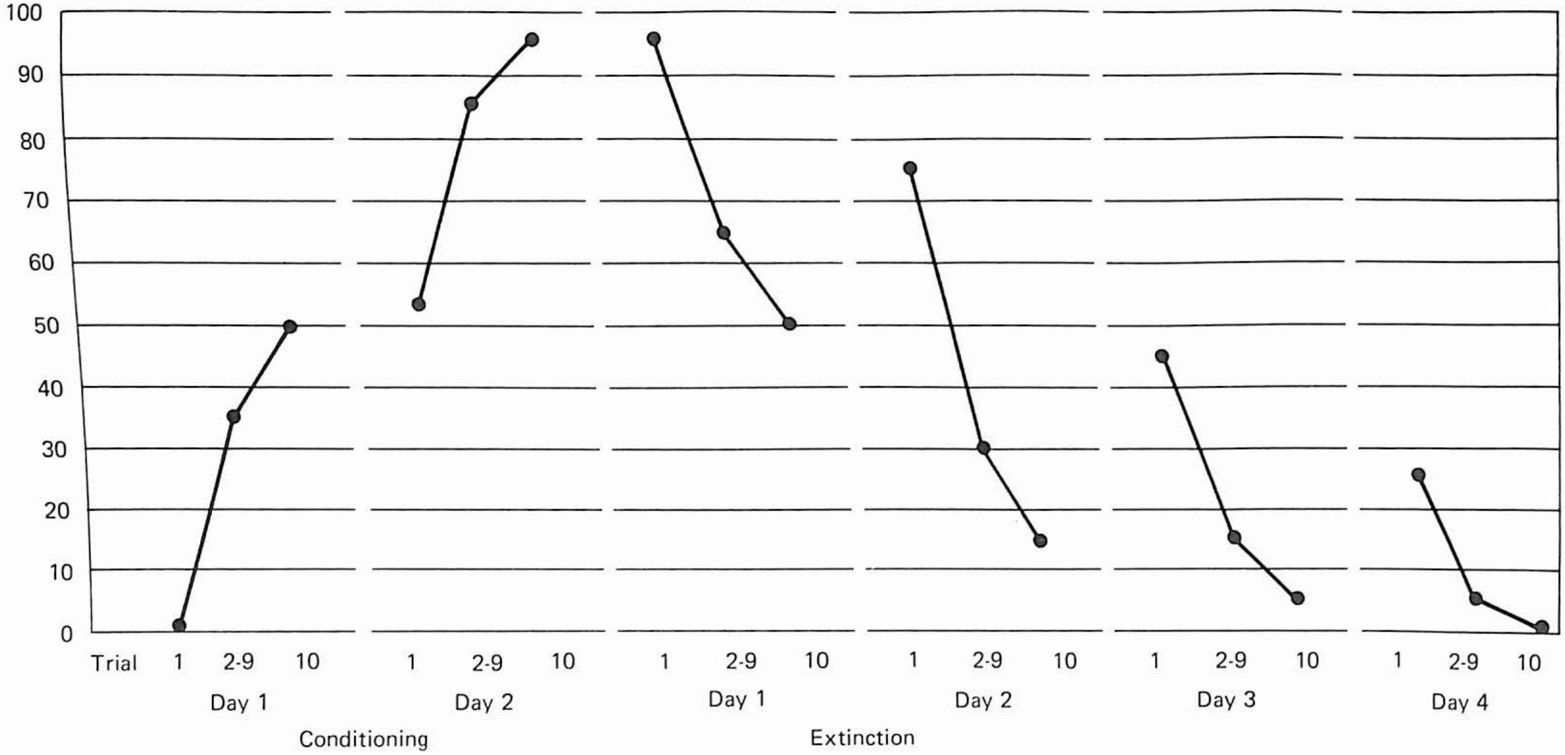

Figure 3-2. Idealized conditioning and extinction functions demonstrating negligible forgetting between acquisition sessions (slight increase due to learning on trial 10) and 50 percent spontaneous recovery between extinction sessions.

evidence for this is that reacquisition after extinction to some performance level is faster than original acquisition from that level.[10]

Because extinction does not appear to be the result of a simple reduction in the strength of the positive association from the *CS* to the *CR*, Pavlov suggested that extinction resulted from *inhibition* of the *CR*, that inhibition builds up over the course of successive extinction trials, reducing the level of performance of the *CR* to the *CS*. If inhibition is assumed to dissipate over a retention interval faster than excitatory trace strength, then spontaneous recovery will be observed.

CS-US INTERVAL

By definition, classical conditioning is dual-contingency learning, requiring the pairing of the *CS* and *US*. Since repeated presentation of a *US* alone could lead to changes in the probability of various responses to a *CS* in the absence of pairing (sensitization or pseudoconditioning), it is necessary to employ a proper control group in order to demonstrate classical conditioning. The most appropriate control group appears to be one in which the *CS* and *US* occur in an unpaired manner. True classical conditioning is demonstrated whenever paired presentation of the *CS* and *US* leads to the development of quantitatively or qualitatively different *CR*s compared to the unpaired presentation of an equal number of *CS*s and *US*s. It might be noted that this control group simultaneously controls for both sensitization, which is the product of repeated presentation of the *US*, and habituation, which results from repeated presentation of the *CS*.

Logically, one could pair the *CS* and *US* with a *CS-US* interval of exactly one week. However so far as is now known, there is no case where classical conditioning can be demonstrated with this long a delay between *CS* and *US*. Hence, contiguity of the *CS* and *US* is very important, though sensitivity of conditioning to the *CS-US* interval varies enormously for different types of learning.

There are many possible temporal relationships between the *CS* and *US*. The most important consideration is the time interval between the onset of the *CS* and the onset of the *US*, but the temporal relationship between the offset of the *CS* and onset of the *US* is sometimes also of importance. In *forward conditioning*, the onset of the *CS* precedes the onset of the *US*. In *simultaneous conditioning*, the *CS* and *US* come on simultaneously. In *backward conditioning*, the onset of the *US* precedes the onset of the *CS*.

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[10] J. Konorski and G. Szwejkowska, "Chronic Extinction and Restoration of Conditioned Reflexes: I. Extinction Against the Excitatory Background." *Acta Biologiae Experimentalis*, 1950 (15), 155-70. J. Konorski and G. Szwejkowska, "Chronic Extinction and Restoration of Conditioned Reflexes: III. Defensive Motor Reflexes." *Acta Biologiae Experimentalis*, 1952 (16), 91-94.

The relative effectiveness of these procedures is as follows: Forward conditioning is superior to simultaneous conditioning, and backward conditioning is usually completely ineffective.[11] Presenting the *US* before the *CS* generally does not increase the performance of the *CR* to the *CS*. This is generally functional. However reliable the pairing of *US* and *CS* in backward conditioning, the *CS* has no informational value to the organism as long as it continues to occur *after* the *US*, because the *CS* can only postdict what has already occurred.

The failure of animals to increase their performance of some *CR* to the *CS* in a backward conditioning paradigm does not mean they have not learned the backward association between the *CS* and *US*. Spooner and Kellogg obtained a substantial level of performance of a *CR* after a few backward conditioning trials, but on later trials the frequency of performance of the *CR* began to decrease in the backward (and the simultaneous) conditioning group(s), while it continued to increase substantially in the forward group.[12] Such a finding suggests that the backward conditioning group initially established a positive association that was gradually replaced by a stronger negative association. There is considerable evidence to support this hypothesis that under the backward conditioning paradigm the *CS* may become a conditioned inhibitor, in that animals learn that the *CS* predicts a period in which the *US* will not occur.[13]

The preceding pattern of results has been obtained with transient *CS*s such as flashes of light or tone bursts. When a physical object is presented as the *CS* following an aversive *US*, animals appear to develop a conditioned emotional response to the physical object, despite the use of a backward conditioning procedure.[14] Keith-Lucas and Guttman shocked rats while they were eating, then after a blackout period of from 1 to 40 seconds they presented the rats with a toy hedgehog. On the next day the rats showed stronger avoidance of the toy hedgehog (backward *CS*) than of the shock location (forward *CS*) even with blackout delays as long as ten seconds. Thus, there would appear to be little doubt that backward excitatory associations can be formed and demonstrated by changes in performance under proper conditions.

Cognitively speaking, demonstration of backward conditioning may depend critically on the likelihood that the *CS* caused the *US* (even though the organism's exposure to the *CS* occurred after the *US*). If you are suddenly pinched while you are standing in a room and then the lights flicker, you are not likely to assume that the flickering lights caused the pinch. But if you turn around after you are pinched and discover an acquaintance standing behind you, you are rather likely to assume that he or she caused the pinch. Of course, the mechanism by which humans draw such inferences is probably different from the mechanism that accomplishes analogous differentiations in rats, but the result may be similar.

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[11] Kimble, *Conditioning and Learning*, p. 48. C. E. Osgood, *Method and Theory in Experimental Psychology*. New York: Oxford University Press, 1953, pp. 313-14.

[12] A. Spooner and W. N. Kellogg, "The Backward Conditioning Curve." *American Journal of Psychology*, 1947 (60), 321-34.

[13] See review by N. J. Mackintosh, *The Psychology of Animal Learning*. New York: Academic Press, 1974. pp. 58-60.

[14] T. Keith-Lucas and N. Guttman, "Robust-Single-Trial Delayed Backward Conditioning." *Journal of Comparative and Physiological Psychology*, 1975 (88), 468-76. T. Keith-Lucas, "Passive Avoidance Learning to Stimulus Objects Presented Before or After Shock" (Unpublished master's thesis, Duke University, 1972). B. B. Hudson, "One-Trial Learning in the Domestic Rat." *Genetic Psychology Monographs*, 1950 (41), 99-145.

Another way to characterize the difference between successful and unsuccessful attempts to demonstrate backward conditioning is in terms of the concept of *preparedness* that we discussed in detail in Chapter 2. Rats may be genetically prepared to associate injury with another organism and not so highly prepared, even contraprepared, to associate a flashing light with injury. The use of highly prepared associations may therefore be successful in demonstrating backward conditioning when the use of less prepared associations is completely ineffective.

In forward conditioning there is usually an optimal interval between the onset of the *CS* and *US*. The optimal *CS-US* interval is sometimes on the order of half a second, as in the case of many skeletal *CR*s such as eyelid and flexion responses.[15] For other *CR*s, particularly autonomic ones like salivation, heart rate, and fear in general, the optimal intervals can range from one to ten seconds—and even more for different species. The optimal *CS-US* interval appears always to be on the order of seconds, though both the optimum and steepness of the gradient around the optimum vary over species and types of *CR*s.

The maximum *CS-US* interval that produces conditioning also varies considerably for different species and types of conditioning. Delays longer than a few seconds produce little or no eyelid conditioning, but *CS-US* intervals of tens of seconds or even minutes can produce satisfactory autonomic conditioning, especially in the case of fear. Learned food aversions and preferences can produce satisfactory conditioning with delays of several hours between consumption of the food (*CS*) and the illness or recovery from illness (*US*).[16] There is both an optimal *CS-US* interval and a maximum tolerable *CS-US* interval, but the magnitude of these intervals varies considerably over different types of associations and different species.

A distinction is sometimes also made between *trace forward conditioning*, in which the *CS* goes off considerably before the onset of the *US*, and *delayed forward conditioning*, in which the *CS* terminates with or sometimes after the onset of the *US*. When the interval between the onsets of *CS* and *US* is long, the delayed procedure generally produces more effective conditioning than the trace procedure. To some extent the delayed procedure pairs the *CS* and *US* at a variety of *CS-US* intervals, including the optimal interval. This could certainly account for the superiority of the delayed procedure to the trace procedure. However since the onset or offset of a stimulus attracts more attention than the middle of a prolonged stimulus, even with a delayed procedure, the interval between *CS* and *US* onsets is important.

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[15] Kimble, *Conditioning and Learning*, pp. 155-59.

[16] See review by Mackintosh, p. 62-66.

INTERMITTENT PAIRING

You are driving on an interstate highway at 85 miles an hour. Suddenly you see a state police car parked beside the road ahead. You immediately apply the brakes and slow down because you have learned there is a very high probability that the police will give you a ticket if they catch you going at that speed. Most people also slow down when they encounter warning signals for sharp turns accompanied by low posted speed limits, because attempting to take a turn at too high a speed can cause a car to go out of control.

By contrast, consider the behavior of drivers when they encounter warning signals for a construction zone accompanied by signs to slow down to some lower speed limit. The vast majority of them make little change in speed, because such warnings are only very rarely accompanied by any actual need to slow down. Construction signs tend to get posted at the beginning of an extended period of work on a section of highway and to be left there for a long time, during only a tiny fraction of which there is any need to impede the normal flow of traffic. The *CS* is only infrequently paired with a subsequent *US*, and so the strength of the conditioning is very low. Since the police rarely enforce lower speeds through construction zones, about the only reason the conditioning has any strength is because of generalization from the need to obey other signs and regulations.

Acquisition: Learning and Performance

Although classical conditioning is very likely involved in our driving behavior, such behavior is also highly influenced by higher-level cognitive learning. Nevertheless, experimental study of classical conditioning has demonstrated that intermittent reinforcement substantially interferes with the development of conditioned responses by producing a lower final (asymptotic) level of performance of the *CR* to the *CS*, and possibly also by reducing the rate of approach to the asymptote (though such an effect on learning rather than performance is not established).

A good example of the effects of intermittent pairing of the *CS* and *US* on both learning and performance is provided in a study by Ross of human eyelid conditioning.[17] The *CS* was a light flash, the *US* a brief air puff delivered to the right eye, the *CR* an eyeblink. There were two pairing conditions: continuous (*C* condition) and 50 percent intermittent (*I* condition). In the continuous condition, the *CS* was always followed after .5 seconds by the *US*, while in the 50 percent intermittent condition, the *US* followed the *CS* on only half of the trials (using a random schedule). Although there were only two pairing conditions, five different experimental groups were employed, with some groups switching after different numbers of trials from 100 percent to 50 percent or from 50 percent to 100 percent pairing. The five groups were as follows: group *C* (100 percent pairing for all trials), group *I* (50 percent pairing for all trials), group *C* 100 *I* (100 percent pairing for the first 100 trials followed by 50 percent pairing), group *C* 20 *I* (100 percent pairing for 20 trials followed by 50 percent pairing), and group *I* 40 *C* (50 percent pairing for the first 40 trials followed by 100 percent pairing). The results are illustrated in Figure 3-3.

Ross's results reveal a number of differences between continuous and intermittent pairing in classical conditioning. Ross apparently ran a suffi-

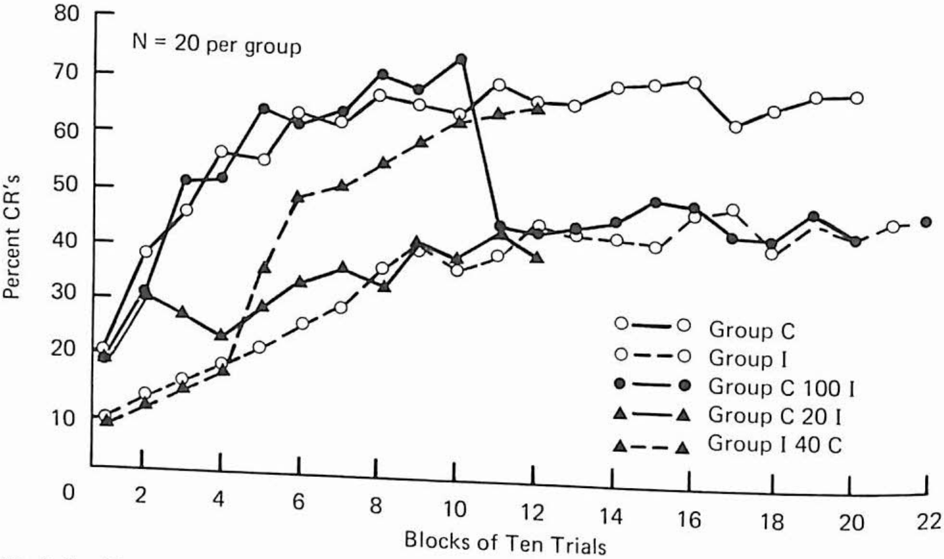

Figure 3-3. Mean percentage of conditioned eyeblinks in successive blocks of ten trials for each of the experimental groups in Ross's study. Group *C* had continuous pairing of the *CS* and *US* throughout training. Group *I* had 50 percent intermittent pairing throughout. Group *C* 100 *I* switched from continuous to 50 percent intermittent pairing after 100 trials. Group *C* 20 *I* switched from continuous to 50 percent intermittent pairing after 20 trials. Group *I* 40 *C* switched from 50 percent intermittent to continuous pairing after 40 trials. (Copyright 1959 by the American Psychological Association. Reprinted by Permission.)

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[17] L. E. Ross, "The Decremental Effects of Partial Reinforcement During Acquisition and the Conditioned Eyelid Response." *Journal of Experimental Psychology*, 1959 (57), 74-82.

ciently large number of trials for all groups to reach asymptotic levels of performance. If so it is clear that the asymptotic level of performance is substantially higher for group *C* (continuous pairing) than for group *I* (intermittent pairing) in this classical conditioning task. This difference in terminal level of performance after extended acquisition training is characteristic of most studies of intermittent pairing in classical conditioning, although there are a number of exceptions.[18]

Second, Ross's study demonstrates that after group *C* 100 *I* reached asymptotic performance under 100 percent pairing, switching them to 50 percent pairing produced an immediate drop to an asymptote appropriate for the 50 percent condition. Such immediate shifts indicate that the asymptotic difference in percentage of *CR*s in the two conditions may be occasioned more by performance factors such as motivation than by the degree to which the organism has learned the association between *CS* and *US*.

Third, switching group *I* 40 *C* from 50 percent to 100 percent pairing at an earlier stage of learning, the 50 percent group requires a substantial number of learning trials before it catches up with the 100 percent group. Also, an early switch from 100 percent to 50 percent pairing produces a higher level of performance of the *CR* in the *C* 20 *I* group than in the *I* group that appears to persist for 50 trials under the 50 percent condition. Such effects suggest a substantial retardation in rate of learning in the intermittent condition when compared to the continuous pairing condition. Unfortunately there is no group in Ross's study that demonstrates how rapidly performance would switch from 50 percent to 100 percent after learning has reached asymptote in the 50 percent condition. An immediate switch would indicate that the 50 percent pairing condition produced learning at asymptote that was as strong as the 100 percent condition, the performance being lower only because of motivational or attentional factors.

In summary, it appears that intermittent pairing in classical conditioning often produces a lower asymptotic level of performance of the *CR* than continuous pairing, but that the difference is the result of motivational or attentional factors rather than differences in associative strength. However, the rate of learning is slower for intermittent than for continuous pairing.

Extinction

It is difficult to compare the rates of extinction following acquisition under continuous and intermittent pairing in such a way that the differences cannot be attributed primarily or solely to the differences in terminal level of acquisition. The complexities of this problem are beyond the scope of this book, but on the whole it would appear that intermittent pairing during acquisition in classical conditioning tends to retard the rate of extinction.[19] One of the clearest demonstrations of this is a study by Hartman and Grant in which the 100 percent pairing condition produced a higher level of performance of the *CR* than various intermittent pairing conditions at the beginning of extinction (end of acquisition), but crossed over the intermittent conditions after a number of trials to produce a lower level of performance later on during extinction.[20]

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[18] See review by Mackintosh, p. 72-75.

INHIBITION

There are both excitatory and inhibitory synapses in the nervous system. Excitatory synapses are synaptic connections that tend to increase the state of activation of the postsynaptic cell, and inhibitory synapses are synapses that tend to reduce the state of activation of that cell. Inhibition is so ubiquitous throughout the nervous system that an account of learning entirely in terms of various degrees of excitatory connection between nodes must almost certainly be incomplete. Pavlov placed considerable emphasis on inhibition in his initial development of classical conditioning, and Russian psychologists continue to be interested in inhibitory phenomena, but until recently, American psychologists have neglected the topic.

Neural Inhibition

The famous Polish psychologist Jerzy Konorski has distinguished four functionally different inhibitory systems in the nervous system.[21] First, there is *reciprocal inhibition,* in which pairs of nervous centers are antagonistic to each other such that excitation of one center inhibits the other and vice versa. Examples include flexion versus extention of the limbs, expiration versus inspiration in breathing, sleep versus waking, and hunger versus satiation. Second, there are *antagonisms* between centers that are not specifically paired—for example, antagonisms of one drive (such as fear) to a variety of other drives (such as thirst, hunger, sex). Third, there is *unidirectional inhibition,* in which one center exerts inhibitory effects on other centers, but these centers do not inhibit it. One example is the inhibition that the cerebral cortex exerts on lower levels of the nervous system. Fourth, there is *lateral inhibition,* in which each neuron inhibits all of its

[19] *Ibid.*

[20] T. F. Hartman and D. A. Grant, "Effect of Intermittent Reinforcement on Acquisition, Extinction, and Spontaneous Recovery of the Conditioned Eyelid Response." *Journal of Experimental Psychology,* 1960 (60), 89-96.

[21] J. Konorski, "Some Ideas Concerning Physiological Mechanisms of So-Called Internal Inhibition," in R. A. Boakes and M. S. Halliday (eds.), *Inhibition and Learning.* New York: Academic Press, 1972, pp. 341-57.

neighbors, usually in proportion to their proximity. Lateral inhibition is found in both sensory and motor systems. One example is in the eye, where lateral inhibition serves to sharpen the contrast between lighter and darker areas, when neurons stimulated by light exert maximal inhibition on nearby neurons in proportion to the activation of the inhibitory neuron. This reduces the rate of firing in neighboring neurons that are not so brightly illuminated, which in turn causes a release in the normal level of lateral inhibition that these less activated neurons exert on the more activeted neurons. The result of all this is a greater difference (enhanced contrast) in the rates of firing of visual neurons at the boundary between lighter and darker regions.

Unconditioned Inhibition

External Inhibition. Performance of a *CR* is reduced in magnitude or probability of occurrence by presentation of a strong (attention-getting) extraneous stimulus.[22] Thus, conditioned salivation to a light will be reduced in strength by simultaneous presentation of a loud noise, as will performance of a leg flexion *CR* under the same conditions. This may have an attentional explanation (the extraneous stimulus reduces the strength of the *CR* by attracting attention from the *CS*) or the extraneous stimulus may initiate an orienting response and activation of this response node laterally inhibits all other response nodes including the *CR*.

Disinhibition. An extraneous stimulus presented during the extinction of a *CR* tends to reduce the extent of the extinction and to restore to some extent the performance of the *CR*.[23] Such disinhibition is difficult to explain in terms of either the stimulus attentional or response inhibitory mechanisms suggested for external inhibition. Many have suggested that both external inhibition and disinhibition have the common action of partially reversing or counteracting the ongoing learning process, whether it be acquisition or extinction. This attractively simple way of unifying the two effects suggests the possibility that external inhibition and disinhibition have a common underlying mechanism; but the nature—even the existence—of that common mechanism is far from clear.

The phenomena of external inhibition and disinhibition demonstrate once again that extinction is not a reversal of the acquisition process, resulting in a simple reduction in the strength of association between the *CS* and *US* or *CS* and *CR*. Imagine a point in extinction at which the probability of performing the *CR* is the same as at some point during original acquisition. An extraneous stimulus presented to an animal during acquisition produces a reduction in the performance of the *CR* (external inhibition). Presentation of the same extraneous stimulus at the comparable point during extinction produces an increase in the performance of the *CR* (disinhibition). These unconditioned inhibitory phenomena in conjunction with spontaneous recovery and other phenomena led Pavlov to conclude that extinction involved some additional (inhibitory) process rather than being a simple reduction in strength of the trace established by the acquisition process.

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[22] Pavlov, *Conditioned Reflexes.*

[23] *Ibid.*

Conditioned Inhibition

Conditioned inhibition has been of considerably greater interest to psychologists than unconditioned inhibition and the subject of considerably more research. The typical paradigm for demonstrating conditioned inhibition in classical conditioning is to pair the conditioned stimulus (C) with the unconditioned stimulus (U), but when C is accompanied by a conditioned inhibitory stimulus (I), the compound is not followed by U. Under such conditions, many organisms learn to produce the *CR* in the presence of C, but not to produce it in the presence of the compound $C + I$.

The concept of condition inhibition was first developed and experimentally demonstrated in Pavlov's laboratory.[24] In one experiment an automobile horn served as the *CS* for a salivary *CR*. After conditioning to the horn had been established, trials were introduced in which the horn was accompanied by the ticking of a metronome and the food *US* was withheld. Label the nonoccurrence of U as $\sim U$. After a number of trials the salivary *CR* to the compound stimulus diminished, though the horn *CS* alone could still evoke salivation.

A conditioned inhibitor (I), prevents the performance of the *CR* in conjunction with the stimulus C with which it was originally compounded. However, Pavlov also demonstrated that I will function as a inhibitor of the same *CR* when it is paired with other condition stimuli that have been associated to the same *CR* but that have never previously been paired with the inhibitor I.[25] That is, pairing C with U, B (another *CS*) with U, and $C + I$ with $\sim U$ (the nonoccurrence of U) will cause I to exert an inhibitory effect on the performance of the *CR* when $B + I$ is presented.

The previous two demonstrations of conditioned inhibition rely on what Rescorla calls the *summation test*, where a stimulus is shown to be a conditioned inhibitor by demonstrating that $C + I$ yields a lower level of performance of a *CR* than does C alone.[26] The other generally accepted way to demonstrate that a stimulus is a conditioned inhibitor is to show that pairing it with the *US* produces slower learning of a *CR* to the stimulus I than the learning of a *CR* to a previously neutral stimulus *A* (produced by pairing *A* with the *US*). Pairing a conditioned inhibitor with a *US* produces very substantial *negative transfer*, that is to say, the rate of acquisition of a *CR* to a previously inhibitory stimulus is extremely slow.[27]

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[24] *Ibid.*

[25] *Ibid.*

[26] R. A. Rescorla, "Pavlovian Conditioned Inhibition." *Psychological Bulletin*, 1969 (72), 77-94.

As previously discussed, one way to establish that *I* is an inhibitory stimulus is to consistently fail to pair *I* with *U* under conditions where some other stimulus *C* is consistently paired with *U*; however such a perfect negative correlation is not necessary to establish *I* as a conditioned inhibitor. Any substantial degree of negative correlation between *I* and *U* will result in *I* becoming a conditioned inhibitor of the *CR* related to *U*.[28]

The generality of inhibition produced by a conditioned inhibitor has not received much systematic investigation, but Konorski presents rather convincing evidence that the inhibition is relatively specific to a particular *US* and its associated *CR*, rather than a general inhibition of all responses.[29] Furthermore, the Russian psychologist Asratian demonstrated that when two responses have been conditioned to the same *CS*, it is possible to extinguish or inhibit one of the responses while retaining the other.[30] This indicates that the inhibition must be specific to a particular *US*, its associated *CR*, or both, rather than being an inhibition of the *CS* node or a general inhibition of all responses or all conditioned responses.

After conditioning has reached a high level, in the delayed or trace procedure, when the onset of the *CS* precedes the onset of the *US* by several seconds, dogs will often delay the performance of the *CR* until near the end of the *CS-US* interval. Pavlov called this delay of the *CR* until just before the onset of the *US inhibition of delay*, and it has been widely replicated in many types of classical conditioning with many species.[31] Recently Rescorla has used the summation method to support Pavlov's claim that the onset of the *CS* and the early part of the *CS-US* interval does act as a conditioned inhibitor.[32]

WHAT IS LEARNED

In the first place it should be emphasized that whatever conditioned response is measured, it is only an indicator of the strengthening of associations between central nodes, perhaps between *CS* and *US* nodes or between *CS* and *CR* nodes. In most classical conditioning situations, one can choose to measure a variety of different emotional and behavioral responses that will be changed by the *CS* in probability, magnitude, or latency of elicitation. What is being learned in classical conditioning is not primarily the association of a *CS* to one particular *CR*, but the association of the *CS* and the *US* or *CS* to a set of *CR*s.

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[27] Konorski, "Ideas Concerning Physiological Mechanisms."

[28] See review by A. R. Wagner and R. A. Rescorla, "Inhibition in Pavlovian Conditioning: Application of a Theory," in Boakes & Halliday, *Inhibition and Learning*, pp. 301-37.

[29] Konorski, *Integrative Activity of the Brain*. Chicago: Universtiy of Chicago Press, 1967. pp. 335-40.

[30] E. A. Asratian, "Genesis and Localization of Conditioned Inhibition," in Boakes and Halliday, *Inhibition and Learning*, pp. 381-97.

[31] See review by Mackintosh, p. 61-62.

[32] R. A. Rescorla, "Inhibition of Delay in Pavlovian Fear Conditioning." *Journal of Comparative and Physiological Psychology*, 1967 (64), 114-20.

There is evidence supporting the hypothesis that what is learned in classical conditioning can be an association between nodes that represent the *CS* and *US*. Such evidence was obtained by presenting a *CS*, such as a tone, followed by shock to the leg, while the organism is paralyzed through use of the drug curare. Curare prevents muscular response by blocking synaptic transmission at the neuromuscular junction, which is the connection from the motor neurons to the muscles. Pairing while the organism is prevented from making skeletal motor responses nevertheless produces classical conditioning as measured by skeletal motor *CR*s made after the effects of the drug have worn off.[33] Furthermore, classically conditioned responses can be extinguished while the organism is prevented from performing the *CR* by curare or mechanical restraint. For example, a leg flexion response to a tonal *CS* that has been followed by shock to the leg can be extinguished by presenting the tone without the shock over a series of trials in which the animal is prevented from making the response by curare or mechanical restraint. Extinction is demonstrated by the lowered probability of responding to the tone when the curare or mechanical restraint is removed.

Of course, this is no proof that the *CS* node is not directly associated to some central skeletal *CR* nodes (even though the *CR* cannot be performed) or to emotional *CR* nodes (emotional responses are not prevented by curare). However, it is parsimonious to assume that what is learned in this case is an association between the *CS* and *US*, and that the various components of the *CR* can come as a result of learning this pairing.

As will be discussed in the section on higher-order conditioning, evidence also exists that the direct association between the *CS* and *CR*s can be learned as well as associations between *CS* and *US*. Evidence from sensory preconditioning, to be discussed in a later section, supports the capacity to form associations between two stimulus nodes. Thus, both *S-S* and *S-R* associations are probably formed in classical conditioning.

THE NATURE OF THE *CR*

There is frequently considerable similarity between the *CR* and the *UR*, but they are sometimes far from identical.[34] The *UR* to foot shock in an open cage is flinching followed by jumping or prancing, but the response conditioned to a tone that predicts shock is freezing or crouching, and the similarity between *CR* and *UR* is irrelevant to the demonstration of classical conditioning. Certain components of the *CR* and *UR* may be highly similar qualitatively and differ primarily in quantity, such as conditioned salivation or conditioned leg flexion, but when these responses are examined in detail, especially with respect to temporal patterning, and when multiple aspects of the *CR* and *UR* are examined, it is clear that they generally differ both qualitatively and quantitatively.

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[33] See review by Mackintosh, p. 79-81.

[34] See Mackintosh, p. 100-109.

There is nothing surprising about this, nor is it inconsistent with the assumption that the *CS* becomes associated with the internal representative of the *US*, but it does force a clarification, which is perhaps best illustrated by an example. Through classical conditioning you may associate the sight of certain foods with their taste, but the sight of these foods does not come to have an equivalent internal representation as their taste. That is, you can still distinguish the sight of food from its taste, however strongly they may be associated. Nor do dogs generally bite, chew, and swallow a light *CS* after associating it with food (though they do occasionally lick the light). These are but examples of the important general principle that normal people, and lower organisms as well, can distinguish their thoughts from sensory or motor reality. No one knows for sure how this distinction is represented in the nervous system, but one simple way is illustrated in Figure 3-4.

In Figure 3-4, the *CS'* and *US'* stand for the internal representatives of the conditioned and unconditioned stimuli actually occurring as sensory events. These nodes are activated only by appropriate sensory input, and their associations to and from other internal representatives cannot be

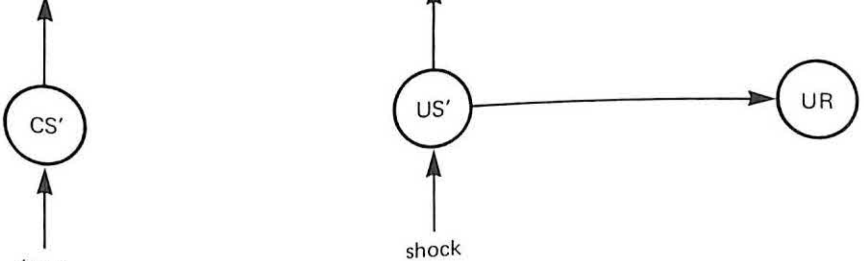

Figure 3-4. Hypothetical model of the internal representation of the important stimuli and responses for classical conditioning. Unlearned (innate) associations are shown by solid lines, learned associations by dashed lines.

modified. The *CS* and *US* stand for the more abstract idea representatives of the *CS* and *US* that can both be activated by appropriate peripheral input and central associative input. From Figure 3-4 we can see that it is quite possible for conditioning to involve an association between internal representatives of the *CS* and *US* at an abstract level without the *CR* necessarily being identical to the *UR*.

Successful adaptation to event sequences may frequently be afforded by using advance warning signals to elicit the same response earlier. However, earlier elicitation of responses highly similar to the unconditioned response is not the only profitable way to make use of warning signals. The nervous system of at least higher organisms appear to possess the ability to use classical conditioning for somewhat more flexible preparation and adaptation.

Response Generalization

When an organism has learned to make a particular *CR* to a *CS*, other responses similar to the *CR* are often evoked, albeit typically with lower probability and amplitude. For example, Kellogg reported that after conditioning with a buzzer followed by shock to the right hind foot of a dog, each of the other three legs occasionally made a flexion *CR* to the buzzer.[35] Moreover, there was a reasonable ordering in the frequency of such generalized *CR*s in the order of presumed similarity: the greatest frequency of *CR*s was in the right hind leg, then the left hind leg, then the right foreleg, and finally the left foreleg. Response generalization in classical conditioning is probably most easily produced when the original *CR* is prevented from occurring but other responses may be considered by the organism to be functionally equivalent or similar to the original *CR*. For example, Bekhterev tied down the foot that normally made a flexion *CR* to the *CS* and found that the dog lifted another foot to the *CS*.[36]

Response Differentiation

The nature of the *CR*s and their time of occurrence with respect to the *CS* frequently changes over the course of conditioning. A *CR* such as the leg flexion, which in the early stages of conditioning may appear as an explosive, high amplitude, short latency response to the *CS*, becomes at later stages a smoothly coordinated, lower-amplitude flexion elicited at much greater latency after the *CS*, usually just before the occurrence of the *US*.

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[35] W. N. Kellogg, " 'Positive' and 'Negative' Conditioning, Without Contraction of the Essential Muscles During the Period of Training." *Psychological Bulletin*, 1939 (36), 575.

[36] V. M. Bekhterev, *General Principles of Human Reflexology*. New York: International, 1932.

HIGHER-ORDER CONDITIONING

Eric is an imaginary friend of mine. He is only six years old, but already he is afraid of the dark because his older brother has a habit of scaring him in the dark. Because he is afraid of the dark, Eric insists on sleeping with his bedroom door open to the lighted hall. One weekend Eric went to stay with his aunt, who had no patience with Eric's fear of the dark. She insisted that he sleep in a completely darkened room with the door closed. Her attitude was approximately, "I'll get rid of that foolishness." Eric's experience that weekend did not extinguish his fear of the dark; what it did was make him afraid of his aunt. Since his aunt was paired with being forced to sleep in a dark room, Eric's fear of the dark transferred to his aunt, a homely example of second-order classical conditioning.

In formal experimental terms the procedure for demonstrating second-order classical conditioning consists of three stages: First, a stimulus, S_1, is paired with some *US* until classical conditioning has been established. Second, another previously neutral stimulus, S_2, is paired with S_1, preferably in the forward S_2-S_1 order for a number of trials. Third, the ability of S_2 to elicit the *CR* previously elicited by S_1 is tested by presenting S_2 in isolation. Second-order conditioning of S_2 to a fear *CR* can be measured indirectly by the extent to which presentation of S_2 interferes with performance of some ongoing operant such as bar pressing to obtain food. Of course, one must perform the appropriate controls to determine that S_2 does not elicit the *CR* in the absence of S_1-*US* and S_2-S_1 conditioning. That is, second-order conditioning, like first-order conditioning, is two-contingency associative learning.

Second-order classical conditioning is more difficult to demonstrate than first-order classical conditioning, but it has been obtained for both appetitive *CR*s such as salivation to food and aversive *CR*s such as fear.[37] It is not hard to understand why it is difficult to demonstrate second-order conditioning, since it is almost exactly equivalent to the design for producing S_2 as a conditioned inhibitor of the *CR*, namely, S_1 is followed by the *US*, but $S_1 + S_2$ is not followed by the *US*.[38] Thus, in second-order conditioning one may be pitting a chain of excitatory associations ($S_2 \rightarrow S_1 \rightarrow US$) against a direct inhibitory connection ($S_2 \rightarrow US$). Apparently there are conditions under which the excitatory association is sufficiently stronger than the inhibitory association that second-order conditioning can be demonstrated.

In principle one might demonstrate even higher-order classical conditioning by adding another stage in which S_3 is paired with S_2. However, not surprisingly, it becomes harder and harder to demonstrate such higher-order conditioning. Because of the successful demonstration of second-order conditioning and sensory preconditioning (discussed in the next section), we assume that all higher-order conditioning occurs in the sense of associating S_{i+1} to S_i, but getting this to produce a *CR* to S_{i+1} is very difficult.

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[37] See review by Mackintosh, p. 19-20.

[38] R. A. Rescorla, "Second-Order Conditioning: Implications for Theories of Learning," in F. J. McGuigan and D. B. Lumsden (eds.), *Contemporary Approaches to Conditioning and Learning.* Washington, D.C.: Winston, 1973, pp. 127-50.

What is learned during the pairing of S^2 (Eric's aunt) and S_1 (a dark bedroom) in second-order conditioning? Rescorla has outlined three different possibilities:[39] First, there is the S_2-S_1 possibility, in which what is learned is an association between S_2 (the aunt) and S_1 (dark room), and since S_1 (the dark room) is associated with the expectation of the *US* (danger) and the *US* is associated to the *CR* (fear), S_2 (the aunt) can elicit the *CR* (fear) by mediation through a chain of intervening associations: S_2-S_1-*US*-*CR*. Second, there is the S_2-*US* posibility, in which the S_2 (the aunt) becomes directly associated to *US* (danger) which is associated to the *CR* (fear), truncating the chain somewhat by comparison to the first theory. Third, there is the S_2-*CR* possibility, in which S_2 (the aunt) becomes directly associated to the *CR* (fear). These possible associations are all illustrated in Figure 3-5.

In a series of ingenious experiments, Rescorla has provided evidence that during second-order fear conditioning, S_2 (the aunt) becomes directly associated to the *CR* (fear). Rescorla discounted the necessity of the S_2-S_1 association by showing that S_2 can still elicit the fear *CR* even after the association from S_1 to fear has been extinguished by presenting S_1 without the *US*. He discounted the necessity of the S_2-*US* association by a somewhat less direct procedure that involved habituation of the response to the *US*

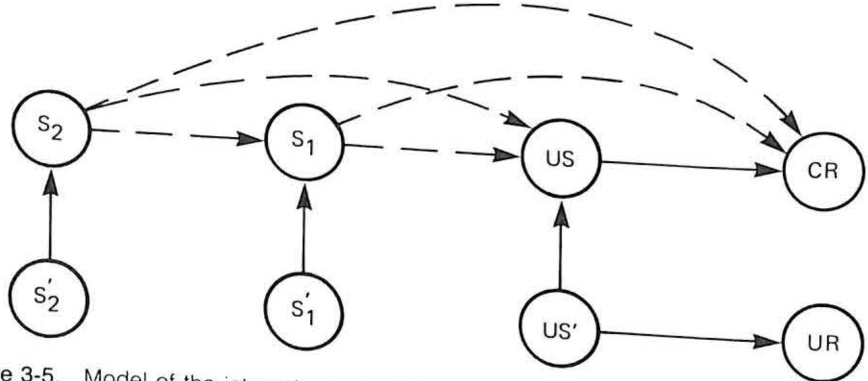

Figure 3-5. Model of the internal representation of the associations formed in second-order conditioning. Note that S_2 is directly associated to the *CR*, so that extinction of the S_1-*US* and S_1-*CR* links in the chain does not extinguish the ability of S_2 to evoke the *CR*. Learned associations are shown by dashed lines, innate (unlearned) associations by solid lines.

(which was a milder noise warning signal rather than a shock to initiate a fear response). Such a habituation to the *US* retards first-order conditioning of S_1 to the fear *CR*, but it has no effect on second-order conditioning. Thus, the capacity of the *US'* to elicit the fear *UR* is not critical to the continued performance of a second-order fear *CR*. Figure 3-5 shows that this last demonstration does not definitely rule out an S_2-*US*-*CR* chain.

Thus, although the S_2-S_1 and S_1-*US* associations are probably formed, there is also probably a direct association formed between S_2 and the *CR* (or possibly S_2-*US*-*CR*). Under the conditions of Rescorla's experiment, the direct connection from S_2 to the *CR* demonstrates second-order fear conditioning even after fear of S_1 was extinguished. Thus, Eric may remain afraid of his aunt after he loses his fear of the dark.

SENSORY PRECONDITIONING

What would have happened had Eric visited his aunt *before* he became afraid of the dark? Let's assume that he slept in a darkened room with the door closed at his aunt's house in the same situation, and that he remembers this fact about visiting his aunt. After he becomes afraid of the dark, will Eric be afraid to visit his aunt? If Eric has learned and remembered the association between visiting his aunt and sleeping in a dark room, he may indeed be afraid to visit his aunt, even though the order of the two associations is reversed from the prior example.

The learning that occurs when S_2 (the aunt) and S_1 (dark room) are paired prior to associating S_1 with a *US* (danger) is known as *sensory preconditioning*. Sensory preconditioning is somewhat more difficult to demonstrate than second-order conditioning, and it may be of a lesser magnitude, but it is demonstrably a reliable phenomenon.[39]

In sensory preconditioning, extinguishing the S_2-S_1 (aunt-dark room) link also extinguishes the capacity of S_2 (the aunt) to elicit the *CR* (fear).[40] What is learned appears to be a chain of associations from S_2 to S_1 and from S_1 to *US* or the *CR* rather than direct association from S_2 to *US* or the *CR*. This chain of associations is illustrated in Figure 3-6. The *US* and *CR* could not have been conditioned to S_2 during the pairing of S_2 and S_1, so this result is not surprising. However, it might have happened that during S_1-*US* (dark room-danger) conditioning, S_1 evoked S_2 (the aunt) via a backward association, which caused S_2 to become associated directly to the *CR* (fear). Apparently this does not happen.

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[39] *Ibid*. R. C. Rizley and R. A. Rescorla, "Associations in Second-Order Conditioning and Sensory Preconditioning." *Journal of Comparative and Physiological Psychology*, 1972 (81), 1-11. See also review by G. Razran. *Mind in Evolution*. Boston: Houghton Mifflin, 1971, pp. 186-207.

[40] See Mackintosh, p. 100-109.

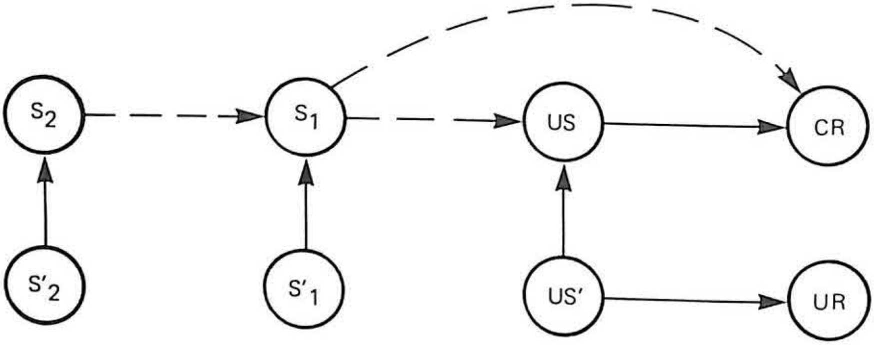

Figure 3-6. Model of the internal representation of the associations formed in sensory preconditioning. Note that S_2 is only indirectly associated to the *CR* via a chain of associations, so that extinction of the S_1-*US* and S_1-*CR* links will also extinguish the *CR* to S_2. Learned associations are shown by dashed lines; innate (unlearned) associations by solid lines.

Sensory preconditioning is different in several ways from first-order classical conditioning. First, backward sensory preconditioning (presenting S_1 before S_2) is successful far more often than backward first-order conditioning (which is often unsuccessful). Second, sensory preconditioning may be facilitated by a somewhat longer delay between S_2 and S_1 than the optimal delay between S_1 and *US* in first-order conditioning. Finally, sensory preconditioning appears to be primarily restricted to birds and mammals. It has not been demonstrated with lower vertebrate species such as fish and amphibians, and is difficult or impossible with reptiles, but simple classical conditioning *can* be demonstrated for fish and much more primitive species. Rabbits also have so far resisted preconditioning (one of many experimental validations of the truth of the popular phrase "dumb bunny").

There is evidence that attention to S_1 is of primary importance in sensory preconditioning.[41] Prior habituation of the orienting response to S_1 depresses sensory preconditioning severely, but prior habituation of the orienting response to S_2 has little effect, perhaps because pairing S_2 with S_1 partially restores attention to S_2, as assessed by the orienting response to S_2. The importance of adequate orientation and attention to S_1 in sensory preconditioning is underlined by the fact that using S_2 stimuli of high intensity and long duration, which interfere with attention and orienting to S_1, also interferes with learning the association between S_2 and S_1.

STIMULUS GENERALIZATION

If a tone of a particular frequency (say, 1000 hz) is used as the *CS* in a classical conditioning experiment, a tone of similar frequency (900 or 1100 hz) will evoke the *CR* with a probability and/or intensity that decreases systematically with decreasing similarity of the test *CS* to the originally trained *CS*.[42] A plot of the strength of conditioning as a function of distance of the test *CS* from the originally trained *CS* is known as a *stimulus generalization gradient*.

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[41] G. Razran, *Mind in Evolution*, pp. 186-207.

DISCRIMINATION

If, instead of conditioning a single tone *CS* to the *CR*, one employs differential conditioning with a 1000 hz tone as the positive *CS* (*CS*+) followed by the *US* and a 2000 hz tone as the negative *CS* (*CS*−) not followed by the *US*, then organisms will come to produce the *CR* in response to the *CS*+ and withhold (inhibit) the *CR* in response to the *CS*−. This capacity for discriminative responding in classical conditioning results from the capacity to establish the *CS*− as a conditioned inhibitor, as discussed previously. Furthermore, the generalization gradient obtained for differential conditioning will also be somewhat steeper and asymmetrical, falling off more sharply in the direction of the *CS*− than in the opposite direction, away from the *CS*−.[43] Even the peak of the gradient may be slightly displaced away from the *CS*+ in the direction opposite from that of the *CS*−. All of this suggests that the *CS*− has an inhibitory generalization gradient around it that summates with the excitatory gradient around the *CS* + yielding the net tendency to produce the *CR*. Generalization and discrimination will be discussed in more detail in conjunction with instrumental conditioning.

SUMMATION

When two *CS*s that have been separately conditioned to the same *CR* are presented together, the probability or intensity of the *CR* is often greater than to either stimulus alone.[44] If the two excitatory *CS*s lie on the same dimension, such as tones of different frequency, and if each *CS*+ produces an excitatory generalization gradient around it, it ought to be possible to produce summation of the two excitatory generalization gradients for intermediate stimuli. Moore has demonstrated just such an effect in conditioning rabbits to tones of 1200 and 2400 hz and obtaining a summation effect in the form of a greater frequency of performance of the *CR* to an intermediate *CS* of 1600 hz than to either of the original *CS*s.[45]

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[42] Bekhterev, *General Principles of Human Reflexology*.

[43] J. W. Moore, "Stimulus Control: Studies of Auditory Generalization in Rabbits," in Black and Prokasy, *Classical Conditioning II*, pp. 206-30.

[44] Kimble, *Conditioning and Learning*, p. 87.

[45] Moore, "Stimulus Control."

OVERSHADOWING

Pavlov found that when two stimuli, such as a light and a tone, were used as a compound *CS* in classical conditioning, the more salient (noticeable) of the two can often overshadow the less salient and reduce the capacity of the less salient stimulus to elicit the *CR*.[46] Specifically, if *U* is the *US*, *M* the more salient *CS*, and *L* the less salient *CS*, overshadowing has occurred when the strength of the *L-U* association is less following conditioning with the compound *M* + *L* as the *CS* than with the single stimulus *L*. Pavlov concluded that the stronger of two component stimuli would overshadow the weaker stimulus to varying degrees depending upon the relative intensities of the two stimuli.

All other factors being equal, the greater the intensity of the stimulus, the greater its salience. However, there are other factors that influence the attention-getting value of a stimulus and the likelihood of its becoming a *CS* that will elicit a *CR* in classical conditioning. A greater novelty or a greater innate capacity to be interesting (whatever that might mean) is a factor over and above intensity. For example, I suspect that a flashing light would be a more salient visual stimulus in a classical conditioning task than a steady light of equal or even greater intensity, despite the fact that the total energy in the steady light exceeds that in the the flashing light. (The only supporting studies that I know of on this concern imprinting.) Of course, the flashing light might initiate greater neural activity than the steady light, which would permit one to hold to a psychological intensity hypothesis with respect to salience.

The salience of a stimulus is also affected by its validity for predicting the *US*. Wagner, Logan, Haberlandt, and Price compared the extent to which a light stimulus acquired control over a *CR* under two conditions.[47] In both conditions the light *CS* was followed by reinforcement on 50 percent of the trials, and in both conditions two different tones were used used as *CS*s. In the correlated condition, one of the tones predicted reinforcement 100 percent of the time; the other consistently predicted nonreinforcement. In the uncorrelated group, each tone predicted reinforcement with the same 50 percent reliability as the light stimulus. In the uncorrelated group where the light was as valid a predictor of reinforcement as the tones, the light acquired substantial capacity to elicit the *CR*, but in the correlated group the light was completely overshadowed by the more valid tone *CS*.

Sometimes overshadowing is mutual. That is, each of two cues partially overshadows the other, which results in less stimulus control over the *CR* by each component than in control groups in which either cue is used as the

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[46] Pavlov, *Conditioned Reflexes*.

[47] A. R. Wagner, F. A. Logan, K. Haberlandt, and T. Price, "Stimulus Selection in Animal Discrimination Learning," *Journal of Experimental Psychology*, 1968 (76), 171-80.

CS without the other. In most classical conditioning studies, however, overshadowing has more frequently tended to be unidirectional—that is one of the stimuli is more salient than the other, and partially or completely overshadows it, and there is no tendency for the less salient stimulus to overshadow the more salient.[48]

BLOCKING

The degrees to which stimulus element *B* overshadows stimulus element *A* in *AB* compound training depends upon the relative salience of *B*, which is largely determined by its predictive validity. Therefore it would appear that prior training with *B* alone, in which *B* was established as a consistent predictor of the *US*, would increase the salience of *B* and thus create greater overshadowing of *A* during subsequent compound *AB* training. Such learned overshadowing, first demonstrated by Leon Kamin, was given the name *blocking*.[49]

CONFIGURING: CHUNKING IN CONDITIONING

In Chapter 1 we discussed the important capacity of human associative memory for chunking, which is the ability to form vertical associations from two or more existing nodes to a new, previously unspecified node. This results in the new chunk node standing for the set of constituent nodes. Largely as a result of work by Russians on *configuring* of compound conditioned stimuli, there is evidence that a capacity for chunking also exists in some species of animals below man. For the last 40 years, about the only American psychologist who appears to have appreciated the theoretical significance of configuring has been Gregory Razran.[50]

Successful demonstration of configuring (chunking) requires that a compound of two or more stimuli produce a *CR* that the constituents of that compound have no ability to elicit above background level. For simplicity let's consider a compound composed to two stimuli, S_1 and S_2, that together elicit the *CR*, but that separately have no such capacity. In the absence of any plausible attentional or motivational-performance explanation, it seems most plausible to assume that S_1 and S_2 have formed vertical associations to a chunk node that stands for the compound. This chunk is associated with the *CR*, but the constituents have no net excitatory association to the *CR*. This situation is illustrated in Figure 3-7.

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[48] L. J. Kamin, "Predictability, Surprise, Attention and Conditioning," in B. A. Campbell and R. M. Church (eds). *Punishment and Adversive Behavior*. Englewood Cliffs: Prentice-Hall, 1969, pp. 279-96. N. J. Mackintosh, "An Analysis of Overshadowing." *Quarterly Journal of Experimental Psychology*, 1971 (23), 118-25.

[49] L. J. Kamin, " 'Attention-Like' Processes in Classical Conditioning," in M. R. Jones (ed.), *Miami Symposium on the Prediction of Behavior: Aversive Stimulation*. Miami: University of Miami Press, 1968, pp. 9-33. Kamin, "Predictability, Surprise, Attention and Conditioning."

[50] Almost all the material discussed in this section was taken from the review by Razran, pp. 207-23.

There are two basic procedures for obtaining configuring. The first, called *differential contrasting*, involves pairing the compound *CS* with the *US*, and on other trials presenting each component without the *US*. Such a procedure explicitly extinguishes any association from the individual constituents to the *CR*, by not pairing the components with the *US*.

There is a second procedure, *prolonged conditioning* of the compound stimulus to the *CR* without contrasting, that produces configuring with surprising consistency. (It should be noted that success in the configuring phenomenon requires many more trials than ordinary classical conditioning. In the early stages of such conditioning, using either procedure, there is considerable association of each individual component to the *CR*, and only after prolonged training is the configuring phenomenon obtained, wherein the compound alone elicits the *CR*.)

The reason that configuring can be obtained without differential contrasting is probably functional. The same elements recur in different combinations throughout the life of an organism and are associated with a variety of different *CR*s. To the extent that an organism forms a *CR* to the most distinctive *CS* which is associated with a *US*, that organism will probably have learned what is most appropriate and will not be forming associations that are subject to considerable prior (proactive) and subsequent (retroactive) interference.

Configuring has been demonstrated with both simultaneously presented components and successively presented components, but it seems to be somewhat more difficult to form a chunk for successively presented components than for simultaneously presented components. Birds and mammals demonstrate both simultaneous and successive configuring, but it takes

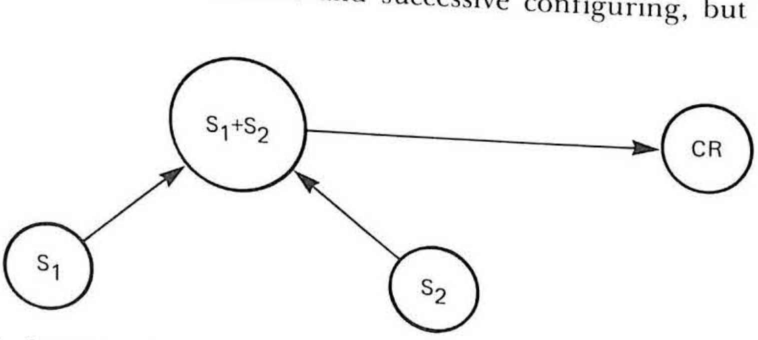

Figure 3-7. Formation of a chunk node ($S_1 + S_2$) to stand for the compound S_1 and S_2 in configuring experiments. By conditioning, this chunk node can be associated to the *CR* node without any direct association from the S_1 or S_2 nodes to the *CR* node.

about four times as many trials to inactivate constituents with successive configuring than it does to inactivate constituents with simultaneous configuring.

That configuring is a higher form of learning has been demonstrated by both phylogenetic comparisons and the results of brain lesions. By and large primates configure much more rapidly than dogs, dogs more rapidly than rabbits, guinea pigs, hedgehogs, etc. Most mammals configure more rapidly than birds, but some species of birds (crows, for example) are superior to some species of mammals (the dumb bunnies again). Although there have been successful demonstrations of successive configuring in a couple of fish under the differential contrasting procedure, the general rule is that fish and amphibians do not configure.

Although elementary classical conditioning frequently survives lesions of the association cortex, both existing configured associations and the capacity to demonstrate new configuring are apparently destroyed by such lesions. Apparently configuring is dependent upon the association cortex, while simple conditioning may be both retained and acquired after decortication. The capacity for chunking is such an important addition to the capacity of associative memory it is tempting to speculate that the basic function of the cerebral cortex is to provide just this chunking capacity and the associations involving such chunks.

Chunking has also been demonstrated by Astratian[51] in conjunction with context-dependent conditioned inhibition of the following type: In one context, C, stimulus A is associated to the performance of one CR (CR_1) and the inhibition of another CR (CR_2). In a different context, D, A is associated with inhibition of CR_1 and the performance of CR_2. Since this phenomenon has only been demonstrated in higher animals, it is most plausible to assume that this takes place through the formation of two chunk nodes representing $C + A$ and $D + A$, which can have different associations without disastrous interference.

SUMMARY

1. Classical conditioning is a change in an organism's behavior (performance of a CR) in response to a stimulus (the CS) as a result of previously *pairing* with another stimulus (the US). Changes in response to repeated presentation of the CS (habituation) or of the US (sensitization) must be excluded by comparison to a control group receiving an equal number of unpaired occurrences of the CS and US.
2. Extinction is elimination of the CR as a response to the CS that results from repeated presentation of the CS not paired with the US.

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[51] Asratian, "Genesis and Localization of Conditioned Inhibition."

3. Forward conditioning (*CS* then *US*) produces a higher level of performance of the *CR* than backward conditioning (*US* then *CS*), but there is evidence to indicate that associations can also be formed in the backward direction.
4. There are both optimum and maximum tolerable *CS-US* intervals in classical conditioning, but they vary from seconds to hours for different types of conditioning.
5. Intermittent pairing of the *CS* and *US* probably retards the rate of learning, but prolongs subsequent extinction.
6. Extinction is not a simple reduction in the strength of association between the *CS* and *US*, but appears to result from the development of inhibition of the *CR*.
7. A stimulus, *I*, becomes a conditioned inhibitor of a *CR* when it is presented with a *CS* and not followed by the *US*.
8. Inhibition also appears to be responsible for suppression of response to the *CS*− in discrimination learning and for the delay in the performance of the *CR* following *CS* onset with a long *CS-US* interval.
9. Both *S-S* associations from the *CS* node to the *US* node and *S-R* associations from the *Cs* node directly to the *CR* node can be formed in classical conditioning, higher-order conditioning, and sensory preconditioning.
10. Although the *CR* is usually similar to the *UR*, there are often some differences, and the *CR* should probably be considered to be a response resulting from anticipation of the *US*.
11. Classical conditioning exhibits stimulus generalization, which is a tendency for stimuli that are similar to the *CS* to evoke the *CR* with greater probability or intensity the greater the degree of similarity.
12. The stimulus generalization gradient in classical conditioning can be made to decline more steeply from the *CS*+ by discrimination training with a *CS*− that is similar to the *CS*+ but not followed by the *US*. If only a single *CS*− is employed, the stimulus generalization gradient will have a steeper decline from the *CS*+ in the direction of the *CS*−, and the peak frequency of responding may be displaced slightly to the other side of the *CS*+.
13. Classical conditioning exhibits summation, which is a greater frequency or intensity of performance of the *CR* to the combined presence of two *CS*s (which have been separately conditioned to the same *CR*) than to either *CS* in isolation.
14. A *CS* with greater innate salience or learned predictive validity will overshadow or block a less salient or less predictive *CS* in classical conditioning.
15. In higher organisms a compound *CS* appears to form a chunk or

configuration that becomes associated to the *CR* after extended training, while its components are not associated to the *CR*. This may occur by specification of a new concept node to represent the chunk in a way that has important basic similarities to all concept learning in human beings.

16. Configuring is a form of associative learning that apparently exists only in the cerebral cortices of higher vertebrates.

4 Instrumental Conditioning

OBJECTIVES

1. To point out that the three basic contingencies in instrumental conditioning—stimulus, response, and reinforcement—generally refer to classes of events and not to single specific events. The learned response class is an *operant*, a set of responses each of which achieves an equivalent result in the external world.
2. To describe the different types of instrumental conditioning: reward, punishment, escape, and avoidance training.
3. To demonstrate that instrumental conditioning has the same or analogous properties as classical conditioning. To facilitate this comparison, the topics and order of sections of Chapter 3 are the same as the first 16 sections of Chapter 4.
4. To discuss what is learned in instrumental conditioning, including (a) Thorndike's Law of Effect as a precise formulation of the *S-R* learning hypothesis and (b) a precise statement of the cognitive expectancy hypothesis.
5. To discuss stimulus generalization and discrimination learning, including treatment of the important role of attention in instrumental conditioning.
6. To distinguish between the somatic and autonomic nervous systems and to discuss this distinction in relation to classical and instrumental conditioning, including a discussion of biofeedback as an aid in controlling autonomic responses, heart rate, and muscle tension.
7. To discuss the relationship between classical and instrumental conditioning and to present two theories—cognitive expectancy and *S-R* reinforcement—that provide an integrated understanding of both forms of conditioning.

"Oh, aren't you a nice girl, Ingrid, sharing your cookie with little Abe! Your little brother is going to love you so much, and I am very proud of you. Would you like another cookie?" Add to this scenario generous amounts of affection, repeat (somewhat lighter) variations of it several thousand times, and you have some idea of the enormous amount of instrumental training Ingrid had to overcome to demonstrate normal sibling rivalry with her brother. That she still managed to demonstrate it after Abe got to be about 2½ years of age is testimony to the irascibility of the human spirit (hers and Abe's, at least). However, Abe did get 2½ years of loving bliss, and that was a pretty nice way to begin life. Compared to the start my next younger brother—and many other second children too—get in life, Abe was very lucky. No doubt Ingrid was born gentler than I, but of course I believe that the instrumental reward training she received for being nice to Abe helped somewhat.

In any event, this training is an everyday example of an instrumental conditioning paradigm. There are three basic contingencies in instrumental conditioning: the stimulus (Abe, perhaps all children, or people in general), the response (sharing and other kinds of loving behavior), and the reinforcement (parental attention, love, praise, and, in this instance, another cookie). Note that in this case, as in almost all examples of instrumental conditioning outside the laboratory, none of the three contingencies is identical on every trial.

The *stimulus* refers to a *class* of different stimulus situations that have something in common. In this case it is Abe, but it could be some other person. The more general one wishes the learning of some behavior to be, the more general should be the set of stimulus situations in which the desired behavior is rewarded. If I want Ingrid to learn to share with people in general, I should be sure to reward her for sharing with many different people of different ages. If I want to be sure that she does not just share when she knows I am there to see it, I should be particularly alert for opportunities to reward her sharing when she is not aware of my presence, and so on. Fortunately, there is usually considerable (stimulus) generalization of learned behavior beyond the specific situation(s) in which learning took place.

The *response* refers to a *class* of different specific motor movements that achieve some common objective, such as giving Abe some food or giving anything nice to Abe or even so general a goal as "making Abe happy." Obviously, generalization of instrumental conditioning to such a broad class of responses as "doing something that makes Abe (or any person) happy (smile, laugh, etc.)" depends upon a large amount of additional learning about what makes Abe (or other people) happy, but as humans grow up they acquire ever more complex knowledge and habits that build on earlier learning of more elementary knowledge and habits.

Lower animals also demonstrate considerable *response generalization*—that is, they do not learn just one specific sequence of muscle movements when they are instrumentally conditioned. Response generalization is learning to perform any of a broad class of functionally equivalent responses that will achieve a certain goal and produce positive reinforcement. Consider a monkey that has learned to pick up a square object to find food underneath. Either hand may be used, and there may be considerable variation in the exact details of the response from trial to trial. Furthermore, if both hands were restrained, a hungry monkey would use its feet, head, or body to displace the object and get at the food. The response learned in instrumental conditioning is generally a large class of muscle movements that the organism regards as functionally equivalent with respect to achieving a certain goal.

Such a range of responses that achieves a common goal is often called an *operant* (instrumental conditioning is frequently referred to as *operant conditioning*). In instrumental conditioning the organism operates on its environment to produce some change. By contrast, classical conditioning is sometimes called *respondent conditioning*, because the animal increases the probability of certain responses, but these responses do not necessarily change the external world as the responses in operant conditioning do. Furthermore, although a classically conditioned response is also not absolutely identical from trial to trial, the range of variation in the *CR* is typically much narrower for classical than for instrumental conditioning. But whether one calls instrumentally conditioned behavior *responses* or *operants*, it is important to remember that these responses or operants refer to a *class* of motor movements rather than to a specific sequence of muscular contractions, and that all these behaviors achieve a goal of changing the external world in some way.

The third critical contingency in instrumental conditioning is the *reinforcement* or *reinforcer* (attention, love, praise, food, and the like). A reinforcer is a (stimulus) event that is to some extent a consequence of emitting one of a class of responses in some class of stimulus situations.[1] The reinforcer is also a *class* of events (different kinds and amounts of food, different kinds of praise, or even a class as broad as "something nice"). Many laboratory instrumental conditioning experiments use only a single standard reinforcer, such as food pellet, and reinforcer variety is certainly not essential for learning. However, the evidence indicates that learning based on a variety of reinforcements is more resistant to extinction later, when reinforcement is withheld for a time.

It is not clear exactly how we ought to classify reinforcers, but the following typology expresses the most frequent distinctions: (1) reward (positive reinforcement), (2) punishment (here referred to as negative reinforcement), (3) the termination or withholding of expected rewards (another kind of negative reinforcement in my usage), and (4) the termination or withholding of expected punishments (another kind of positive reinforcement in my usage). When withholding an expected reward or punishment occurs in extinction, it is usually called nonreinforcement. However, when such withholding is contingent on certain responses, it can also be used in combination with reward or punishment for other responses to teach a new habit or to eliminate some component of a previously conditioned response. Chapter 5 contains a detailed discussion of positive and negative reinforcement in relation to appetitive and aversive drives. For the present we shall assume that organisms in a given situation perform responses that they associate with positive reinforcement and do not perform responses that they associate with negative reinforcement. This chapter is concerned with how organisms learn these associations.

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[1] Many psychologists use the term *reinforcer* to refer only to events that strengthen the probability of the responses that produce them. Such psychologists use the term *positive reinforcement* to refer to reward and *negative reinforcement* to refer to the termination of aversive stimuli. According to this usage the onset of punishment, which weakens responses, is not negative reinforcement. It is the termination of punishment which is a negative reinforcer. I find this usage confusing and will use the term *reinforcement* to refer to either positive or negative *consequences* of behavior.

ACQUISITION: CONCEPTS AND PARADIGMS

The four basic instrumental conditioning paradigms are usually distinguished (1) by whether positive (appetitive) or negative (aversive) reinforcing stimuli are used, and (2) by whether the organism is reinforced for making a particular response (emission) or for failing to make a response (omission). The four basic types are the four combinations of these two distinctions.

Reward Training

In reward training an organism receives positive reinforcement for emitting an active response. A hungry animal pressing or pecking a bar to obtain food and a child who learns to make the bed to receive praise or some other positive reinforcement are examples of the reward training paradigm. Animals have also been instrumentally conditioned to make such responses as: pulling a string, running down an alley (maze), choosing the right or left run at the choice point in a T maze, making a sequence of turns in a complex maze, running or jumping through one of two doors. When an animal is first placed in a *go, no-go* situation, it typically sniffs and looks and moves around investigating the environment. Eventually it may accidentally make the response to be rewarded (*CR*)—for example press the bar or go to the other end of the alley—at which time it receives a food pellet. On subsequent trials, the animal will tend to perform the *CR* sooner—that is, with reduced response latency. In a *choice task*, such as the T maze, the animal will make the correct response with higher probability on subsequent learning trials.

Escape and Avoidance Training

In escape and avoidance training, an organism learns to emit a response in order to escape or avoid some aversive stimulus. Examples of this paradigm include: a dog learning to jump over a barrier or to push through a door in order to escape or avoid electric shock, a pigeon learning to peck a key or a rat to press a bar in order to avoid shock or a loud noise. In an *escape* paradigm the aversive stimulus is already present in the situation, and the response to be learned will terminate it. In an *avoidance* paradigm the aversive stimulus will be presented after some period of time unless the response to be learned is performed. Avoidance paradigms are more complex than escape paradigms.[2] In avoidance conditioning the organism is thought to learn the association between the stimulus situation and the subsequent aversive stimulus by a classical conditioning process. The stimulus situation then becomes a danger signal, which the organism learns to escape by performing a particular response.

Omission Training

Omission training consists of rewarding an organism for failing (omitting) to perform a particular response. For example, for every fifteen seconds that a pigeon fails to peck a key, it might be rewarded with food. Omission training has rarely been investigated, except for a recent series of experiments by Uhl and his colleagues.[3]

Punishment Training

In punishment training some overt response an organism already emits to a stimulus (in a situation) is punished by presentation of some aversive stimulus. The punished response is typically established by learning, but it might be an innate response elicited by cues in the stimulus situation. A rat that has learned to lick a tube to obtain water reinforcement might suddenly be punished by electric shock for licking the drinking tube. The rat must learn to refrain from licking to avoid punishment. As an example of punishing a response that is probably innate, rats have been punished by electric shock for stepping down from a small platform onto a grid floor. Such punishment typically produces a large amount of learning on the first trial. A frequently used measure of learning in this task is the latency with which the rat steps off the platform. In one such experiment performed by Chorover and Schiller the median latency of stepping down was 1.6 seconds on the trial just before punishment. After one punishment, the median latency increased to 30 seconds.[4]

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[2] D. H. Mowrer and R. R. Lamoreaux, "Avoidance Conditioning and Signal Duration: A Study of Secondary Motivation and Reward." *Psychological Monographs*, 1942 (54), No. 247. R. A. Rescorla and R. L. Solomon, "Two-Process Learning Theory: Relationships Between Pavlovian Conditioning and Instrumental Learning." *Psychological Review*, 1967 (74), 151-82. R. C. Bolles, "The Avoidance Learning Problem," in G. H. Bower (ed.), *The Psychology of Learning and Motivation*, Vol. 6. New York: Academic Press, 1972. M. E. P. Seligman and J. C. Johnston, "A Cognitive Theory of Avoidance Learning," in McGuigan and Lumsden, *Contemporary Approaches*.

[3] C. N. Uhl and E. E. Garcia, "Comparison of Omission with Extinction in Response Elimination in Rats." *Journal of Comparative and Physiological Psychology*, 1969 (69), 554-62. C. N. Uhl and W. O. Sherman, "Comparison of Combinations of Omission, Punishment, and Extinction Methods in Response Elimination in Rats." *Journal of Comparative and Physiological Psychology*, 1971 (74), 59-65. C. N. Uhl, "Eliminating Behavior with Omission and Extinction after Varying Amounts of Training." *Animal Learning and Behavior*, 1973 (1), 237-40. See also M. D. Zeiler, "Eliminating Behavior with Reinforcement." *Journal of Experimental Animal Behavior*, 1971 (16), 401-05.

Free Operant Versus Discrete Trials

An animal in a Skinner box is usually free to make a response at any time (e.g., press a lever) and receive reinforcement (e.g., a food pellet). In such *free operant* tasks, a response does not remove the animal from the situation. By contrast, a dog placed in a shuttle box where it must jump over a barrier to escape or avoid electric shock is operating on a *discrete trial* basis. Once the animal is placed in the situation, it must make a response within some period to escape or avoid the shock. Similarly, a rat on a Lashley jump stand is placed on the starting platform at the beginning of each discrete trial and must jump through one of two doors. One of the doors is open and may lead to food, and the other is locked and produces the punishing experience of bumping into a locked door and falling into a net below. In discrete-trial tasks, we measure the strength of conditioning by the probability, amplitude, or latency of the *CR* on each trial. In free operant tasks, we measure the strength of conditioning by the rate at which the *CR* is performed. In each case we must remember that performance is a function of attention and motivation as well as of learning.

Shaping

Psychologists who study operant conditioning have developed some very clever training techniques. Basic to these is probably *shaping.* Instead of dropping a pigeon into a Skinner box and waiting for it to peck a key before administering reinforcement, the experimenter watches the animal and initially reinforces it for standing in the part of the cage that is reasonably close to the key. Once the pigeon has begun to stand close to the key, it is reinforced only for holding its head in a position relatively close to the key. The range of possible head positions is then progressively narrowed so as to converge on the key. After such behavior has been shaped, rewards are delivered only when the pigeon pecks (anywhere in the vicinity of the key). This is followed by a narrowing of the acceptable pecking targets converging on the key.

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[4] S. L. Chorover and P. H. Schiller, "Short-Term Retrograde Amnesia in Rats," *Journal of Comparative and Physiological Psychology,* 1965 (59), 73-78.

Shaping procedures like this can greatly enhance the speed of acquisition for instrumentally conditioned responses with a low *a priori* probability of being emitted. Shaping has considerable practical significance in training animals and possibly also young children, though in all but the youngest children verbal instruction is usually a much more efficient method than shaping for eliciting initial responses.

EXTINCTION

Extinction of Reward Training

The conjunction of the situational stimuli and a response in instrumental conditioning is analogous to a compound *CS* in classical conditioning, and the reinforcer is analogous to the *US* in classical conditioning. Following this analogy, extinction in instrumental conditioning consists of failing to present the reinforcement when the organism performs the previously conditioned response in the situation. As was true in classical conditioning, such a procedure eventually reduces to zero the probability that the subject will perform the *CR*. Once again, extinction is much faster than forgetting for eliminating instrumentally conditioned responses. Also, the response-independent occurrence of reinforcement during extinction retards the rate of extinction, just as random presentation of the *US* retards the rate of extinction in classical conditioning. In general, the less the situation is changed from acquisition to extinction, the slower the extinction, but since organisms apparently don't attend to many of the attributes in the experimental context, changing these attributes from acquisition to extinction has no effect on rate of extinction.[5]

In consonance with the retarding effect of response-independent reinforcement on extinction, Uhl has demonstrated that deliberately rewarding a rat for not performing an operant for 20 seconds is less effective in eliminating the operant than a conventional extinction procedure, even though the rate of performing the operant eventually reached the same low level under both procedures. Furthermore, when random, response-independent rewards were subsequently introduced, rats given omission training showed little increase in the rate of performing the operant, whereas extinguished rats rapidly returned to their previous high rate of performance.[6] So if the parents of an overly demanding child want that child to learn to demand less attention, these results suggest that a complete withholding of attention might be a slightly more rapid way to reduce demands for attention. However, since a conscientious parent will eventually want to give the child a great deal of attention, a more effective technique might be to deliberately reward the child for refraining from such demands for a modest period of time.

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[5] See Mackintosh, *Animal Learning*, pp. 472-75 and 407-08. R. A. Rescorla and J. C. Skucy, "Effect of Response-Independent Reinforcers During Extinction." *Journal of Comparative and Physiological Psychology*, 1969 (67), 381-89. R. A. Boakes, "Response Decrements Produced by Extinction and by Response-Independent Reinforcement." *Journal of Experimental Animal Behavior*, 1973 (19), 293-302.

Extinction of Escape and Avoidance Training

What constitutes an extinction procedure for escape and avoidance training that is analogous to that used in reward conditioning? A traditional extinction procedure in escape and avoidance conditioning has been to eliminate completely the possibility of the aversive stimulus: no aversive stimulus is presented regardless of whether or not the organism performs the operant. Many studies have shown that avoidance responses are much more difficult to extinguish than comparable escape responses. They are also generally much more difficult to extinguish than reward-conditioned responses.

However, there is substantial reason to question whether the complete removal of the aversive stimulus constitutes the appropriate analogue to extinction in reward conditioning.[7] Rather, the appropriate extinction procedure is to present the aversive stimulus independent of the operant's performance. Such a procedure produces far more rapid extinction of avoidance conditioning than is produced by the more traditional extinction procedure. Extinction following avoidance training will be discussed in more detail in Chapter 5.

SPONTANEOUS RECOVERY

Spontaneous recovery of a *CR* after extinction has been demonstrated in instrumental as well as classical conditioning. Ellson trained rats to perform a bar-pressing operant. One day later the rats were extinguished to a criterion of five minutes without performing the operant. After extinction, various groups of rats were returned to the situation following delays of from five minutes to three hours. All groups showed some spontaneous recovery of bar pressing, and the amount of recovery increased as a function of the delay since the end of extinction.[8]

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[6] C. N. Uhl, "Eliminating Behavior with Omission and Extinction after Varying Amounts of Training." *Animal Learning and Behavior*, 1973 (1), 237-40.

[7] See Mackintosh, *Animal Learning*, pp. 331-37 and 337-39.

[8] D. G. Ellson, "Quantitative Studies of the Interaction of Simple Habits: I. Recovery from Specific and Generalized Effects of Extinction." *Journal of Experimental Psychology*, 1938 (23), 339-58.

DELAY OF REINFORCEMENT

Billy, four years old, sometimes wanders from his own yard into the street. When his father comes home he asks if Billy has gone into the street that day. He spanks Billy if he has and gives him some little treat if he has not. Somehow, despite the application of this consistent instrumental conditioning procedure, Billy keeps wandering into the street. What's wrong? Of course several things might be wrong, but one serious problem is the long delay between the act of going into the street and the administration of the reinforcement. However reliable the relationship between an action and some consequence, if the delay of reinforcement is too long, there will be no learning.

Because adult human beings have language, it is possible to inform them of the action that led to reward or punishment in more or less immediate contiguity with administration of the reward or punishment. This is usually effective for an adult, but it is progressively less effective the younger the child.

A delay of from five to ten seconds between the execution of an elementary response such as a bar pressing or turning left in a T maze and the delivery of a reward, such as food, can substantially reduce the rate at which an organism acquires the correct response. The dependence of the learning rate on the delay of reinforcement is called the *delay of reinforcement gradient*. Similar deleterious effects have been found for delay of punishment and delay of offset of an aversive stimulus in escape training.[9] All conditioned responses show some sensitivity to delay of reinforcement, but it can vary enormously for different associations and conditions.

The classic studies of Wolfe and Perkins investigated how fast rats learned to make the correct turn at the choice point of a T maze as a function of the delay between making the response and receiving the reward.[10] The delay was achieved by detaining the rats in presumably identical delay chambers for different periods following both correct and incorrect choices. Perkins even randomly interchanged his two presumably identical delay boxes over trials to further insure that the delay compartment gave no clue as to the correctness of choice. Rate of learning declined progressively with increases in delay of reinforcement up to 60 seconds, but some learning was still achieved with delays of reinforcement as long as 60 seconds. In a more difficult black-white discrimination learning task, where rats had to choose either the black or the white alley independent of position, Grice attained an even sharper dependence of learning on the delay of reinforcement, obtaining essentially no learning with a ten-second delay between response and reinforcement.[11]

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[9] See Mackintosh, *Animal Learning*, pp. 155-59.

[10] J. B. Wolfe, "The Effect of Delayed Reward upon Learning in the White Rat." *Journal of Comparative Psychology*, 1934 (17), 1-21. C. C. Perkins, Jr., "The Relation of Secondary Reward to Gradients of Reinforcement." *Journal of Experimental Psychology*, 1947 (37), 377-92.

The main reason instrumental conditioning was so adversely affected by increases in the delay of reinforcement in these tasks appears to be the increased opportunity for associative interference during the delay. Spence, Revusky, and Garcia argue that other responses an animal performs in the delay can acquire a greater strength of association to the reinforcement than the operant defined by the experimenter.[12] In support of this notion, Spence cites several studies that suggest that the performance of competing responses during delay intervals plays a large role in the deleterious effects of delay of reinforcement. One of these studied rats' learning to run to the end of an alley maze to obtain food as a function of delay of reinforcement and the width and height of the alley (the length was the same for both groups). The basic hypothesis was that the more confining alley (two inches wide, three inches high) would discourage the animal from turning away from the food cup during the delay, while the more spacious alley (17 inches wide 11.5 inches high) would encourage performance of potentially interfering responses during the delay interval. The results were exactly as expected. There was no difference in learning speed for rats running in the confined or spacious alley with zero delay of reinforcement between running the alley and receiving the reward, but there was a substantial difference in favor of the rats in the confined alley between the groups that received a ten-second delay of reinforcement.

Three experiments by Lett offer even more striking support for the importance of associative interference as a fundamental factor in the delay of reinforcement gradient. Lett was able to obtain substantial learning of a black-white discrimination in a T maze with a delay of reinforcement as long as one minute. Lett also obtained substantial learning of a position habit in a T maze (making a right or left turn) with a delay of reinforcement of up to 60 minutes. The distinctive feature of Lett's experimental design is that rats were removed completely from the T maze and housed in their home cage during the delay interval. Rats that had made the correct choice were rewarded at the end of the delay interval (after being placed in the start box of the T maze), which eliminated any opportunity for the rats to perform interfering responses in the experimental situation after performing the critical choice response. Prevention of competing responses in the experimental situation appears to permit instrumental conditioning with extremely long delays between the response and reinforcement. Indeed, when Lett kept the total delay of reinforcement constant and permitted different groups of rats to remain in the choice alley for 0, 15, or 60 seconds before removal to the home cage to spend the remainder of the two-minute delay, learning decreased systematically according to the length of time spent in the maze.[13] It might be noted that these results also support the hypothesis that it is the *conjunction* of the stimulus situation and the operant that is associated to reinforcement in instrumental conditioning. The opportunity to perform interfering responses in a totally different situation produces much less associative interference than the opportunity to perform competing responses in the same situation.

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[11] G. R. Grice, "The Relation of Secondary Reinforcement to Delayed Reward in Visual Discrimination Learning." *Journal of Experimental Psychology*, 1948 (38), 1-16.

[12] K. W. Spence, *Behavior Theory and Conditioning*. New Haven: Yale University Press, 1956, pp. 155-63. S. Revusky and J. Garcia, "Learned Associations over Long Delays," in G. H. Bower (ed.), *The Psychology of Learning and Motivation*, Vol. 4. New York: Academic Press, 1970, p. 1-84.

These findings would appear to have analogues in human experience. For example, imagine yourself attempting to improve the picture on your TV set by banging on it (in a restrained manner) in different places, looking for any subsequent improvement in picture quality. Just as you tap one particular location, the telephone rings and you rush to answer it. Five minutes later you come back and observe that your TV picture has substantially improved. The chance that you will associate the improvement with the tap in the preceding location is of course enormously greater than it would be if you had been tapping the TV set at various locations during the five-minute interval. Our lives have many different contexts, and what happens in one context is both less interfering and less well integrated with events in another context than with other events in the same context.

The longest delays of reinforcement producing learning have been obtained in learned food preferences and aversions, in which the ingestion of food is followed perhaps hours later by pleasant or unpleasant internal consequences. In these experiments extremely effective conditioning has been obtained with delays as long as 12 hours.[14] One reason for the very different sensitivity to delay of reinforcement is that animals are especially prepared to learn associations between new foods and pleasant or unpleasant internal consequences. A rat eats one new substance at a meal and some hours later becomes sick. If an animal's nervous sytem is constructed so that it only associates food with illness or recovery from illness, and if it eats only one new food at a time, then there can be no interference with the formation of an association between a food and illness or recovery. By contrast, muscular responses that produce changes in the environment tend to produce consequences more or less immediately, and an organism is likely to make a number of responses every few seconds. For such associations it is functional for an animal to have a relatively steep delay of reinforcement gradient, and the potential for interference is so large that one would be surprised to find any other result.

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[13] B. T. Lett, "Delayed Reward Learning: Disproof of the Traditional Theory." *Learning and Motivation*, 1973 (4), 237-46. B. T. Lett, "Visual Discrimination Learning with a One-Minute Delay of Reward." *Learning and Motivation*, 1974 (5), 174-81. B. T. Lett, "Long Delay Learning in the T Maze." *Learning and Motivation*, 1975 (6), 80-90.

[14] J. C. Smith and D. L. Roll, "Trace Conditioning with X-Rays as the Aversive Stimulus." *Psychonomic Science*, 1967 (9), 11-12.

The delay of reinforcement gradient is analogous to the *CS-US* interval in classical conditioning. The evidence also suggests that the reason learning falls off with increasing delay of reinforcement has nothing directly to do with the motivational factors involved in experiencing primary rewards and punishments. What is critical is the delay of informative feedback regarding "what causes what." If a rat is detained in a delay box after it turns left or right in a T maze before it is allowed to proceed to the goal box, the rat can learn the maze despite long delays, provided the delay boxes for the left and right turns are distinctive in some way—for example, black versus white.[15] Under such circumstances there is a relatively immediate pairing of left turn with detention in, say, the black delay box and a relatively immediate pairing of the black box with entering the goal box containing the reward. Such a chain of associations is somewhat more difficult to learn than a single direct association, but each association in the chain has a relatively short delay of feedback.

Many noncognitive experimental psychologists have called such distinctive cues that mediate long delays of reinforcement *secondary reinforcers*, on the belief that such stimuli acquire reinforcing properties. The evidence for such a belief will be examined in more detail in Chapter 6. For the moment we will regard the cognitive delay of feedback theory and the secondary reinforcement theory as equivalent, but it is important to note that what is essential for learning is the contiguity between critical events and not the delay of primary reinforcement, though the latter can have an effect on performance.

INTERMITTENT REINFORCEMENT SCHEDULES

Schedules of Reinforcement

So far we have assumed that the contingency between an operant and a reinforcement was 100 percent—that is, that every time the organism performed the operant it was eventually reinforced. Such *continuous reinforcement* is probably only typical of instrumental conditioning in the laboratory. Billy is not always punished for playing in the street, nor is Ingrid always rewarded for being nice to her brother. Whenever the probability of some reinforcement is less than 100 percent, the instrumental conditioning is said to be on a *partial* or *intermittent reinforcement schedule*.

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[15] C. C. Perkins, "The Relation of Secondary Reward to Gradients of Reinforcement." *Journal of Experimental Psychology*, 1947 (37), 377-92. G. R. Grice, "The Relation of Secondary Reinforcement to Delayed Reward in Visual Discrimination Learning." *Journal of Experimental Psychology*, 1948 (38), 1-16. See also Kimble, *Conditioning and Learning*, pp. 153 and 193-94.

In a discrete-trial task, such as a hungry rat running down an alley from the start box to the goal box, one might place food in the goal box on only 70 percent of the trials.

In a free-operant procedure there are a variety of different possible schedules of reinforcement. The four most basic types are fixed-interval, variable-interval, fixed-ratio, and variable-ratio. In the *fixed-interval* schedule an animal receives a reward for the first operant performed after a period of time (such as 30 seconds) has elapsed since receiving the last reward. In a *variable-interval* schedule, the time interval is varied from trial to trial. It might be 10 seconds, 20 seconds, 30 seconds, 40 seconds, or 50 seconds. Of course, the animal only gets reinforced at the end of the interval (whatever it might be on that trial), after it makes a response. With a *fixed-ratio* schedule, an animal gets reinforced after it has made a certain number of responses. With a *variable-ratio* schedule, that number varies randomly around some average.

Interval and ratio schedules are not completely unnatural laboratory tasks. Fixed-interval schedules are somewhat analogous to working for an hourly, daily, or monthly wage. Some work must (usually) be performed in the period to get paid, but the bare minimum will usually suffice (until one is fired). Fixed-ratio schedules are analogous to piece work, such as payment of $.50 for each bushel of apples picked.

At first glance one might think that intermittent reinforcement would produce slower learning of the *CR*, less reliable performance of the *CR* even after learning is complete, and faster extinction when reinforcement was completely withdrawn. The data regarding instrumental conditioning under intermittent reinforcement do give some support for slower learning, but the ultimate rate of performance of the operant is often higher under intermittent than under continuous reinforcement, and the resistance to extinction is invariably also greater for intermittent reinforcement.[16] We might well have expected this considering what a high rate of play can be sustained by a slot machine. A slot machine is essentially an intermittent reinforcement device whose intermittent positive reinforcing effect must counteract a continuous cost to play, the knowledge that, on the average, one loses on slots, plus negative social attitudes toward gambling.

The rate of responding is lower the longer the interval in a fixed-interval schedule or the longer the average in a variable-interval schedule.[16] There is an optimum ratio with fixed and variable-ratio schedules. The highest rate of responding is obtained for some intermediate ratio (which varies for different species). In pigeons the maximum response rate is obtained for ratios of approximately 50 responses per reinforcement.

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[16] Mackintosh, *Animal Learning*, pp. 73-75, 159-61, 166-82, 189-90, and 434-67. J. A. Nevin and G. S. Reynolds (eds.), *The Study of Behavior*. Glenview, Ill.: Scott, Foresman, 1973, pp. 203-11. See also D. Robbins, "Partial Reinforcement: A Selective Review of the Alleyway Literature since 1960." *Psychological Bulletin*, 1971 (76), 415-31.

Vastly higher rates of responding can be obtained with ratio schedules than with interval schedules, which should not be surprising. However, on high ratio schedules, where a large number of responses is required to produce a reward, performance can break down entirely—the animal simply ceases to perform the operant.

Some interesting patterns of responding have also been observed: With fixed-interval schedules the tendency of animals to make few responses until near the end of the interval and then to make a burst of them prior to reinforcement suggests that animals learn the time schedule of reinforcement. Responses are more evenly distributed throughout a variable-interval schedule.

Acquisition

Reinforcing a response less often than 100 percent of the time appears to produce a slower rate of acquisition than a continuous reinforcement schedule, much like intermittent pairing of the *CS* and *US* in classical conditioning.[17] However, results in this area vary enormously for different tasks, conditions, and performance measures of learning (choice versus latency, for example). It is reasonable to assume that each nonreinforced trial acts to some extent as an extinction trial, once a moderate degree of association has been established between the response and reinforcement.

Some learning psychologists believe that intermittent pairing of the *CS* and *US* interferes more with the rate of acquisition in classical conditioning than a comparable percentage of reinforcement does in instrumental conditioning. The most striking evidence for this belief is that classical conditioning has not been obtained with a reinforcement percentage of less than 25 percent, but that instrumental conditioning can be obtained with much lower percentages of reinforcement. Such evidence is sometimes offered in support of a difference between the underlying mechanisms in classical and instrumental conditioning.[18]

Consideration of the distinction between learning and performance indicates that this conclusion is not justified. As we discussed in the previous chapter, asymptotic performance of the *CR* in classical conditioning is substantially lowered by a lower percentage of pairing between *CS* and *US*. The evidence is not conclusive, but this effect on asymptotic performance probably represents a motivational-performance difference rather than any difference in learning (associative strength).

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[17] Mackintosh, *Animal Learning*, pp. 189-90.

[18] Kimble, *Conditioning and Learning*, p. 103.

By contrast the motivational-performance factors at asymptote in instrumental conditioning are often such as to produce a much higher rate of conditioned responding at lower percentages of reinforcement than in classical conditioning. That is, a lower percentage of reinforcement produces a higher rate of responding. Since classical and instrumental conditioning are affected very differently by such motivational-performance factors at asymptote, it is reasonable to assume that the same influences are present at earlier stages of learning. It may be that an organism performing after several hundred trials of classical conditioning with a probability of 0.2 or less of pairing *CS* and *US* has established a strong association between the *CS* and *US*, but that this association has no effect on performance.

Extinction

John's car starts the first time he switches on the ignition. Frank's car sometimes starts immediately, but more often it requires a number of ignition attempts. One day something goes wrong with the ignition system of both cars, and they simply will not start. Who is more likely to run down his battery before calling the garage? Obviously, Frank, since he expects his car to be rather difficult to start. The same thing happens in the laboratory in the extinction of responses following continuous, as opposed to intermittent, reinforcement: Extinction is far more rapid following 100 percent reinforcement than following lower percentages of reinforcement. The lower the percentage of reinforcement during acquisition, the larger the number of extinction trials required. This phenomenon is very reliable, and it holds for both classical and instrumental conditioning.

The rate at which a *CR* extinguishes has often been taken as a measure of the strength of conditioning. On that basis, one might expect a *CR* that has been reinforced 100 percent of the time to be more resistant to extinction than one that has been only intermittently reinforced (say 50 percent of the time). Somewhat surprisingly, for birds and mammals this is very definitely not the case, at least after a moderately high criterion of learning has been achieved. If continuously and intermittently reinforced groups are both run to a common acquisition criterion, the number of trials required to a common extinction criterion is substantially greater in the case of the intermittently reinforced group.[19]

There are many hypotheses regarding the intermittent reinforcement extinction effect. Lloyd Humphreys, one of the two discoverers of the effect, and apparently the first to recognize its theoretical significance, offered the *expectancy hypothesis*, which is that continuous reinforcement leads to the expectancy of being reinforced on every trial, and when this expectation is not met, extinction is rapid.[20] By contrast, intermittently reinforced animals do not expect to be reinforced on every trial and so a much longer period of zero-level reinforcement is required to produce extinction.

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[19] Mackintosh, *Animal Learning*, pp. 73-75 and 434-67.

Closely similar to this are the *discrimination hypothesis* and the *generalization-decrement hypothesis*. The discrimination hypothesis is that the change from acquisition to extinction is more difficult to discriminate for the intermittent reinforcement group than for the continuous reinforcement group. This is little more than a restatement of the expectancy hypothesis. The generalization-decrement hypothesis specifies that during acquisition under intermittent reinforcement, the concept representing nonreinforcement on the previous trial becomes associated with performing the *CR*. Since this nonreinforcement node is activated during extinction, extinction is more similar to acquisition under the intermittent reinforcement than to acquisition under continuous reinforcement. Hence, there is less generalization decrement from acquisition to extinction under intermittent reinforcement.

A particular version of generalization decrement is the *frustration hypothesis* developed by Amsel, according to which the animal becomes frustrated by nonreinforcement.[21] There is evidence for the existence of a frustration drive in intermittent reinforcement of alley maze running, in that animals run faster on trials following nonreinforcement than on trials following reinforcement. Such frustration has become conditioned to performance of the *CR*. This has not happened during continuous reinforcement. According to this hypothesis, in intermittent reinforcement frustration is conditioned to the *CR* and it is this frustration that helps maintain performance of the *CR* during extinction. But in continuous reinforcement, frustration has *not* been conditioned to the *CR* and so accelerates extinction by generalization decrement.

A rather different hypothesis, is the *response unit hypothesis*, according to which an organism on a 50 percent reinforcement schedule has learned to produce a *CR* that is essentially equivalent to two responses on a continuous reinforcement schedule. In a 33 percent reinforcement schedule, the learned *CR* is to produce three responses in order to receive reinforcement, etc. If the response units are different, and if the total number of responses were divided by the appropriate number (two for a 50 percent schedule, three for a 33 percent schedule, and four for a 25 percent schedule, etc.), according to this hypothesis one should expect to find a constant number of response units to extinction. In fact, this does appear to produce a more nearly constant number of trials to extinction, though the number of trials to extinction actually declines somewhat with a lower percentage of intermittent reinforcement, rather than rising sharply as it does under the hypothesis that each trial constitutes an opportunity to emit a single response unit.

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[20] L. G. Humphreys, "The Effect of Random Alternation of Reinforcement on the Acquisition and Extinction of Conditioned Eyelid Reactions." *Journal of Experimental Psychology*, 1939 (25), 141-58.

[21] A. Amsel, "The Role of Frustrative Nonreward in Noncontinuous Reward Situations." *Psychological Bulletin*, 1958 (55), 102-19.

The response unit hypothesis suggests that what is learned in intermittent reinforcement is more complex than what is learned in continuous reinforcement, because experiences from several trials are combined into a single chunk. Two phenomena provide some support for this notion. One is that when there is *regular* alternation of reinforced and nonreinforced trials (*R*, *N*, *R*, *N* . . .), the intermittent reinforcement extinction effect is not obtained: extinction is virtually as rapid as after continuous reinforcement.[22] The pattern of responding on alternate trials during training indicates that the animals have somehow learned the alternation concept. For example, with alternating reinforcement at the end of a runway, rats run faster on reinforcement trials than on nonreinforcement trials. This is direct evidence that some higher organisms can learn concepts that incorporate experiences on more than one trial.

Second, Bitterman and his colleagues have shown that the intermittent reinforcement extinction effect is not obtained in some fish and amphibians.[23] This is in sharp contrast to the regularity with which the phenomenon is obtained in birds and mammals. (In fish one can even obtain greater resistance to extinction via continuous reinforcement.) It may be no accident that the split appears to come at precisely the same point on the phylogenetic scale as the dividing line for chunking capacity. Thus, while we cannot say precisely what organisms learn under intermittent acquisition conditions, the locus of the effect on extinction may result from the ability of higher organisms to form more complex concepts that chunk the experiences from several trials.

[22] D. W. Tyler, E. C. Wortz, and M. E. Bitterman, "The Effect of Random and Alternating Partial Reinforcement on Resistance to Extinction in the Rat." *The American Journal of Psychology*, 1953 (66), 57-65. Also see Mackintosh, *Animal Learning*, pp. 448-49.

[23] J. Wodinsky and M. E. Bitterman, "Partial Reinforcement in the Fish." *American Journal of Psychology*, 1959 (72), 184-89. J. Wodinsky and M. E. Bitterman, "Resistance to Extinction in the Fish after Extensive Training with Partial Reinforcement." *American Journal of Psychology*, 1960 (73), 429-34. N. Longo and M. E. Bitterman, "The Effect of Partial Reinforcement with Spaced Practice on Resistance to Extinction in the Fish." *Journal of Comparative and Physiological Psychology*, 1960 (53), 169-72. R. C. Gonzalez, N. Longo and M. E., Bitterman, "Classical Conditioning in the Fish: Exploratory Studies of Partial Reinforcement." *Journal of Comparative and Physiological Psychology*, 1961 (54), 452-56. R. M. Eskin and M. E. Bitterman, "Partial Reinforcement in the Turtle." *Quarterly Journal of Experimental Psychology*, 1961 (13), 112-16. R. C. Gonzalez and M. E. Bitterman, "A Further Study of Partial Reinforcement in the Turtle." *Quarterly Journal of Experimental Psychology*, 1962 (14), 109-12.

The Varied Acquisition Extinction Effect

Most of the hypotheses on extinction after intermittent reinforcement suggest that there is considerable reason to suspect that what is learned in intermittent reinforcement is different from what is learned in continuous reinforcement. This supposition is strengthened by the fact that similar increases in resistance to extinction occur if we vary any of the other conditions that occur during acquisition—for example, the amount of reinforcement from trial to trial, the delay of reinforcement, the number of different reinforcers, the number of response alternatives, stimulus conditions such as the level of illumination, etc.[24] Apparently just about any variation in the conditions during acquisition will produce a slower rate of extinction in birds and mammals. Thus, the *intermittent reinforcement extinction effect* is a special case of the *varied acquisition extinction effect.*

INHIBITION

External Inhibition and Disinhibition

Both external inhibition and disinhibition have been repeatedly demonstrated for instrumentally conditioned responses as well as for classically conditioned responses. For example if a strong extraneous stimulus such as a tone or light is presented to an animal that is bar pressing to receive food, the rate of bar pressing will decrease during presentation of the stimulus and will continue to be depressed for a minute or two after the termination of the stimulus.

As was the case in classical conditioning, the same stimuli that produce external inhibition of an instrumentally conditioned response also produce disinhibition of an extinguished instrumental response. For instance, after a bar pressing response has been extinguished, presentation of a novel stimulus will increase the rate of bar pressing for a short period of time. External inhibition and disinhibition both habituate after repeated presentation of the extraneous stimulus. Finally, Brimer has demonstrated that there is a strict positive correlation between the effectiveness of an extraneous stimulus as an external inhibitor and its effectiveness as a disinhibitor. Thus, the more effective external inhibitors of conditioned responses are also the more effective disinhibitors of extinguished responses.[25]

Conditioned Inhibition

Conditioned inhibition has also been repeatedly demonstrated in instrumental conditioning.[26] The basic procedure for establishing a conditioned inhibitor in instrumental conditioning is to reward the operant under stimulus condition *C*, but not to reward it in the presence of a stimulus that is to become the conditioned inhibitor. Stimulus *C* might be the basic situational cues, such as the inside of a Skinner box, while *I*, the conditioned inhibitor, is an additional stimulus, such as a red light. When the light is on, food cannot be obtained by performing the bar pressing operant, but when the light is off, food can be obtained by performing the *CR*. It appears that conditioned inhibition is the same in both classical and instrumental conditioning.

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[24] Kimble, *Conditioning and Learning,* pp. 286-90.

[25] C. J. Brimer, "Disinhibition of an Operant Response," in Boakes and Halliday, *Inhibition and Learning,* pp. 205-27.

Completing the parallel between inhibition in instrumental and classical conditioning, there is a phenomenon in instrumental conditioning that is analogous to the inhibition of delay found in classical conditioning. Inhibition of delay in classical conditioning is the tendency for organisms to withhold performance of the *CR* after the onset of the *CS* until just before the expected occurrence of the *US*. The analogous phenomenon in instrumental conditioning is that in both fixed-interval and fixed-ratio reinforcement schedules rats and pigeons pause immediately after they receive the reward. The length of the pause is longer the greater the length of the fixed interval or fixed ratio that must elapse between reinforcements.[27]

WHAT IS LEARNED

What is learned in instrumental conditioning must involve some representation of the stimulus situation, since organisms that have learned to perform a conditioned response via instrumental conditioning do not go around performing that *CR* in situations that are radically different from the training situation. Since neither the stimulus situation nor the reinforcement stimulus need elicit anything remotely similar to the *CR* prior to instrumental conditioning, it would appear unreasonable to assert that all that is learned in instrumental conditioning are *S-S* associations between the stimulus situation and the reinforcement, and that the development of that association leads in some indirect way to the performance of the *CR*. Such an assertion would appear logically unreasonable, since a wide variety of *CR*s can be instrumentally conditioned to achieve reinforcement in the stimulus situation.

Two positions concerning what is learned in instrumental conditioning, the *S-R* position and the *SR-K* position (where *K* stands for reinforcement), appear to be reasonable. The *S-R* position was first formulated by Thorndike as a part of the Law of Effect, which is that reinforcing a response *R*c in situation *S* strengthens the association of *S* with *R*c more than mere contiguity strengthens the associations of *S* with other responses (*R*i) that are not followed by reinforcement.[28] Note that according to the *S-R* learning position reinforcement plays an important role in learning, but it is not directly incorporated into associations as a part of what is learned. That is, the expectation of some particular reinforcement is not part of the memory trace itself. According to this position, there is no sense in which an organism has learned which consequences follow performance of responses in various situations. Rather, it simply performs the response that has the strongest association to the stimulus situation. The Law of Effect says that that response will tend to be one that has most reliably produced desirable outcomes (reinforcement) in the past.

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[26] E. Hearst, S. Besley, and G. W. Farthing, "Inhibition and the Stimulus Control of Operant Behavior." *Journal of the Experimental Analysis of Behavior*, 1970 (14), 373-409. See also Boakes and Halliday, *Inhibition and Learning*.

[27] Nevins and Reynolds, *The Study of Behavior*, pp. 203-11. Mackintosh, *Animal Learning*, pp. 166-82.

Presumably we human beings can tell which outcomes will follow from the performance of responses in various situations, and it appears unreasonable to assert that humans perform responses in situations without any idea of their outcomes. Psychologists like Tolman who took a more cognitive approach to the analysis of animal behavior than Thorndike, felt it was more reasonable to attribute much the same *SR-K* expectancy learning capability that humans have to lower animals as well. According to one *SR-K* expectancy theory, the stimulus situation *S* activates propositional nodes representing such expectancies as, "If R_1 is performed in situation *S*, then K_1 will result"; "If R_2 is performed in situation *S*, then K_2 will result"; etc. The activation of such nodes in memory must be accompanied by a performance rule to the effect that the response performed is the one that produces the most desirable outcome of all the responses considered. Tolman and other cognitive psychologists considered it supporting evidence for the *SR-K* expectancy theory that rats at a choice point would often look back and forth at each of the alternative choices as if thinking about the consequences of making each choice, a process known as *vicarious trial and error*.[29] Of course the fact that rats sometimes hesitate and look back and forth at a choice point hardly gives much information concerning the nature of the memory trace (what is learned) or of the thinking processes involved in translating memory into performance.

Somewhat more convincing evidence in support of the *SR-K* expectancy position is the evidence for *latent learning* (which we shall discuss in detail in Chapter 7). Latent learning studies have demonstrated that animals can learn what-leads-to-what in a maze without the ordinary forms of primary reinforcement.[30] For example, if a satiated rat has the opportunity to explore a maze for a time without any extrinsic reinforcement, there is considerable positive transfer when food is placed in a particular location in the maze and the now hungry rat is placed at some other point in the maze. Rats that have had prior opportunity to learn what-leads-to-what in the maze make fewer errors in the course of learning to get from the starting point to the food. Since none of the previous turning responses made by the rat at various points were reinforced or punished during the period of exploration, the *S-R* Law of Effect provides no explanation of this positive transfer. The *SR-K* cognitive theory is that the animal learns which turning responses lead, in various choice situations, to various outcomes (new locations in the maze). Once one of these outcomes is associated with the presence of food, the animal can perform the sequence of responses at various choice points that eventually leads to food.

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[28] E. L. Thorndike, "Animal Intelligence: An Experimental Study of the Associative Processes in Animals." *Psychological Review, Monograph Supplements*, 1898 (2), No. 8.

[29] E. C. Tolman, "Cognitive Maps in Rats and Men." *Psychological Review*, 1948 (55), 189-208.

[30] Kimble, *Conditioning and Learning*, pp. 226-34.

Nor is it necessary for the rats to actually make the turning responses in order to learn what-leads-to-what in a maze. Gleitman and McNamara, and Long and Wike put rats in little cars or baskets and passively moved them through a T maze, sometimes into the correct alley where they received reward, sometimes into the incorrect alley where they received no reward. When the rats were subsequently allowed to make free choices, a substantial number of them performed the correct response on the first trial even though they had not previously made the critical choice response in the situation.[31] As we shall discuss in more detail in Chapter 7, animals can also learn some things by imitation, that is by watching another animal perform responses and receive various consequences as a result. Such learning suggests that at least some animals below humans need not actually make the critical responses in order to learn what-leads-to-what. The imitation phenomenon indicates that the organism needs neither to perform the response nor to receive reinforcement in order to learn what-leads-to-what.

Operants can be extinguished under conditions in which performance of the operant itself is prevented, a phenomenon we shall call *extinction without responding.*[32] The phenomenon is also often called *latent extinction*, but this term erroneously suggests an analogy to latent learning, whereas the appropriate counterpart is learning without responding. For example, if rats that have learned to run a maze to obtain food are placed directly in the goal box that now contains no food, the result is a substantial decrement in the performance of the operant of maze running. Thus, performance of the operant itself is not necessary to obtain either acquisition or extinction.

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[31] H. Gleitman, "Place Learning Without Prior Performance." *Journal of Comparative and Physiological Psychology*, 1955 (48), 77-79. H. J. McNamara, J. B. Long, and E. L. Wike, "Learning Without Response under Two Conditions of External Cues." *Journal of Comparative and Physiological Psychology*, 1956 (49), 477-80.

[32] Kimble, *Conditioning and Learning*, pp. 320-23. See also Mackintosh, *Animal Learning*, pp. 416-17.

Another support for the *SR-K* expectancy hypothesis are *reinforcement contrast effects*. Rats trained to perform operants for a given reward perform worse when switched to a smaller or less preferred reward than rats trained using the smaller or less preferred reward from the beginning.[33] Such contrast effects are difficult to explain with an *S-R* learning hypothesis, which presumes that the animals have not encoded the nature of the reinforcement as part of the *S-R* memory trace. Such contrast effects indicate that rats do encode the reinforcement as a part of what is learned, as the cognitive expectancy hypothesis contends.

Most of the evidence appears to favor the *SR-K* expectancy hypothesis concerning what is learned in instrumental conditioning, at least for birds and mammals, but the evidence is hardly definitive for all tasks and species. Furthermore, the *SR-K* expectancy hypothesis very likely requires a minimal capacity to chunk the *S* and *R* nodes into a common chunk node, and possibly a capacity to chunk the *S, R,* and *K* nodes into a propositional node, and according to data on configuring, species below birds and mammals appear to be unable to do this. It is possible that species that do not configure are conditioned by an *S-R* learning mechanism that is consistent with Thorndike's Law of Effect.

Bitterman made essentially this point when he contended that fish often learn *S-R* associations via Thorndike's Law of Effect while rats learn expectancies. A particularly clear example of this is that goldfish and painted turtles fail to show contrast effects when they are switched from a larger to a smaller reward. In fact, Lowes and Bitterman found that goldfish switched from a large to a small reward after learning was complete continued to perform at the same level as a group maintained on the large reward throughout. Not only was there no momentary depression after the switch, performance *never* deteriorated to the level found for a group maintained on the small reward throughout![34] Figure 4-1 illustrates the general type of result obtained for rats and fish.

THE NATURE OF THE CONDITIONED RESPONSE

When children learn to pick up their toys after playing to achieve a reward such as pleasing their parents, what is learned is not a particular set

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[33] M. H. Elliott, "The Effect of Change of Reward on the Maze Performance in the White Rat." *University of California Publications in Psychology*, 1928 (4), 19-39. L. P. Crespi, "Quantitative Variation of Incentive and Performance in the White Rat." *American Journal of Psychology*, 1942 (55), 467-517.

[34] M. E. Bitterman, "Thorndike and the Problem of Animal Intelligence." *American Psychologist*, 1969 (24), 444-53. M. E. Bitterman, "The Comparative Analysis of Learning." *Science*, 1975 (188), 699-709. G. Lowes and M. E. Bitterman, "Reward and Learning in the Goldfish." *Science* 1967 (157), 455-57.

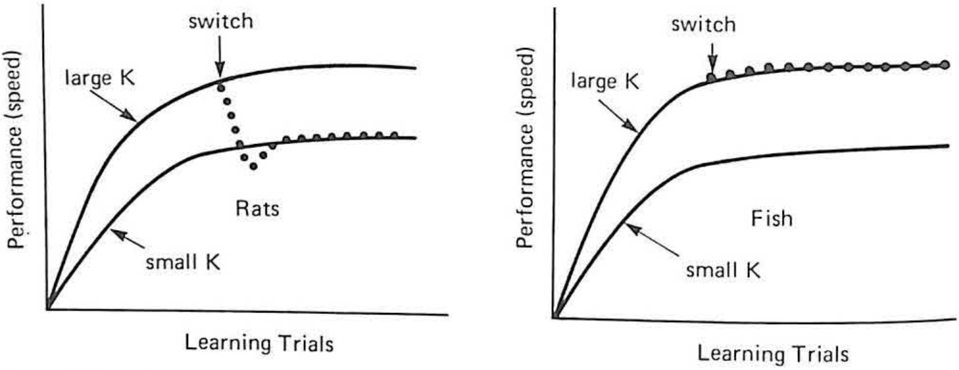

Figure 4-1. The hypothetical performance for rats and fish of switching from a large reward to a small reward after learning is complete (shown by the dotted lines) as compared to performance of animals kept on large or small rewards throughout (solid lines). Note the contrast effect for rats and the eventual shift to a level of performance appropriate for reward magnitude. Note the absence of such effects for fish.

of muscle movements, but the goal to be achieved. In such naturalistic settings, the principal evidence for this assertion is that the particular motor movements differ from situation to situation and that, in nearly identical situations, children will perform the response in different but functionally equivalent ways.

The same conclusion regarding what is learned in elementary instrumental conditioning applies in controlled experimental settings to lower animals. A rat that has learned to press a bar in a Skinner box to obtain a food pellet exhibits substantial variation in the manner of pressing the bar.[35] If it is prevented from pressing the bar with one paw, it will press with the other. If prevented from using any paw, the rat will press with its nose or body, anything to achieve the goal. Rats that have learned to run a maze show almost perfect transfer when they must swim the same maze filled with water.[36]

Closely related to this assertion that what is learned is a functionally equivalent class of responses is the phenomenon of progressive *response differentiation* over the course of instrumental conditioning. Under many conditions the initial occurrences of reinforced responses may be high amplitude, long duration, and uncoordinated responses. As conditioning proceeds, the *CR* typically becomes progressively briefer, less intense, and better coordinated—that is, it becomes the minimally effective response for producing the desired goal. Thus, within the class of responses that are functionally equivalent with respect to achieving one particular goal, there are differences with respect to other goals, in particular conservation of metabolic energy.

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[35] Kimble, *Conditioning and Learning*, pp. 73 and 88-90.

[36] D. A. MacFarlane, "The Role of Kinesthesis in Maze Learning." *University of California Publications in Psychology*, 1930 (4), 277-305.

CHAINING

Organisms can also learn chains of instrumentally conditioned responses, which is analogous to higher-order conditioning. A rat can and frequently does master maze problems in several different stages: typically it first learns to make the correct response at the last choice point before the goal, then it masters the immediately prior turn, etc. A pigeon taught to peck a key illuminated by a red light to obtain food can then be taught to peck a different key in order to turn on the red light.[37]

Wolfe's well-known secondary (learned) reinforcement experiment also illustrates chaining in instrumental conditioning. Chimpanzees first learned to insert discs similar to poker chips into a vending machine that produced a grape when a token was inserted. The chimps were then trained to earn tokens by performing simple instrumental responses, such as lifting a lever or pulling a tray. In these experiments considerable time could elapse between the earning of tokens and the opportunity to insert them into the vending machine to obtain food (primary reinforcement).[38]

Whether the intermediate stimuli, which are obtained as a result of earlier responses (the choice points in the maze that precede the goal, the lighted red key, or the tokens), should be thought of as learned reinforcers that function in some sense similar to primary reinforcers is a matter we shall discuss in Chapter 6. For the moment all that is of concern is that animals can learn chains of instrumentally conditioned responses that are sometimes very long and complex, as in the case of some highly trained circus animals. The limits on chaining capacity for different species at different levels of development of the nervous system, if any, have not been established.

Superstitious Behavior

Since it is typically necessary to initiate a chain of responses, in order to achieve a significant goal, it is not surprising that organisms demonstrate the capacity to learn chains of responses. From a functional standpoint, organisms must be so highly prepared to learn such chains of conditioned responses that under some circumstances such chains are learned even though reinforcement is not contingent upon them.

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[37] Kimble *Conditioning and Learning*, pp. 145-49. Nevin and Reynolds, *The Study of Behavior*, pp. 167-70.

[38] J. B. Wolfe, "Effectiveness of Token-Rewards for Chimpanzees." *Comparative Psychological Monographs*, 1936 (12), No. 60.

In 1948 Skinner discovered that when rewards are delivered by a clock according to a fixed rate and independent of responses, most pigeons will perform highly stereotyped response chains between reinforcements. By speculative analogy to the origins of human superstitions, he labeled such conditioned response chains superstitious behavior.[39]

The explanation for the superstitious conditioning is that some chain of responses was accidentally performed prior to reinforcement. The association of this chain to reinforcement was therefore strengthened, leading to its subsequent repetition, which was also reinforced. If the reward schedule and timing are right, there will be a high probability of reinforcing such a response chain shortly after it is performed. It is easy to see how such a response chain might be learned, even though reinforcement is not contingent upon it. Once such a chain has acquired a certain degree of strength, it cannot be extinguished under the conditions of this experiment unless the organism is set to exhibit a certain variety in its behavioral repertory.

LATENT LEARNING

Latent learning was briefly discussed in a previous section and will be further discussed in Chapter 7. All we wish to point out here is that latent learning in instrumental conditioning is analogous to sensory preconditioning in classical conditioning, assuming that the *US* in classical conditioning is analogous to reinforcement in instrumental conditioning. Latent learning is, by definition, learning that takes place prior to the introduction of reinforcement, and sensory preconditioning is learning that takes place prior to the introduction of the *US*. Hence, successful demonstration of both latent learning and sensory preconditioning provides yet another parallel between classical and instrumental conditioning.

GENERALIZATION

Stimulus generalization can also be demonstrated in instrumental conditioning. Since most tests of generalization are performed under extinction conditions, in which no response to any test stimulus is rewarded, it is desirable to train animals under long variable-interval schedules of reinforcement. The purpose of such a technique is to slow down the rate of extinction radically, permitting assessment of the generalization gradient under conditions where little or no extinction is taking place. Guttman and Kalish employed a variable one-minute interval training schedule with the response key illuminated by light of a particular wavelength (color) for 60-second intervals separated by ten-second dark time-out periods. (In the dark the pigeons did not respond.) Tests of generalization as a function of wavelength were then performed by illuminating the key for 30 seconds with light of some wavelength and recording the number of responses. The results of some of their tests are shown in Figure 4-2.[40]

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[39] B. F. Skinner, " 'Superstition' in the pigeon." *Journal of Experimental Psychology*, 1948 (38), 168-72.

Guttman and Kalish attempted to test whether the steepness of the generalization gradient around any particular *CS* was dependent upon the pigeon's ability to discriminate wavelengths in that region. Wavelength discriminability varies considerably over the spectrum to which the pigeon is sensitive, but the shape of the generalization gradient did not appear to be systematically related to the ability of the pigeon to detect wavelength differences. Under some circumstances one would expect it to be logically necessary for a generalization gradient to be related to the ability of the animal to discriminate one stimulus from another, but according to the Guttman and Kalish study generalization is often far more than a simple failure to discriminate between different *CS*s. With proper training organisms can frequently be trained to discriminate extremely fine stimulus differences, but in the absence of such training generalization gradients spread out enormously beyond the capacity to discriminate different stimuli. Hearst has shown that increasing the amount of training with a single *CS* is sufficient to produce more sharply peaked generalization gradients around the original *CS*.[41] However, what really steepens generalization gradients is specific discrimination training with a negative *CS* (*CS*−) close to the *CS*+.

Some circumstances produce completely flat generalization gradients around the *CS* used during instrumental conditioning. Jenkins and Harrison trained pigeons to peck a key during the presence of a 1000 hz tone, separated by short time-out periods in darkness, much as in the Guttman and Kalish experiment. Under these conditions the tone appeared to acquire no stimulus control over the rate of pecking, since pigeons pecked with equal frequency during generalization testing to tones of any frequency from 300 to 3500 hz. However, under differential conditioning, where pecking was reinforced during presentation of the 1000 hz tone and not reinforced when no tone was present, the typical peaked generalization graident around the 1000 hz *CS*+ was obtained.[42]

[40] N. Guttman and H. I. Kalish, "Discriminability and Stimulus Generalization." *Journal of Experimental Psychology*, 1956 (51), 79-88.

[41] E. Hearst and M. B. Koresko, "Stimulus Generalization and the Amount of Prior Training on Variable-Interval Reinforcement." *Journal of Comparative and Physiological Psychology*, 1968 (66), 133-38. E. Hearst, "Excitation, Inhibition, and Discrimination Learning," in N. J. Mackintosh and W. K. Honig (eds.), *Fundamental Issues in Associative Learning*. Halifax, N.S.: Dalhousie University Press, 1969.

[42] H. M. Jenkins and R. H. Harrison, "Effect of Discrimination Training on Auditory Generalization." *Journal of Experimental Psychology*, 1960 (59), 246-53.

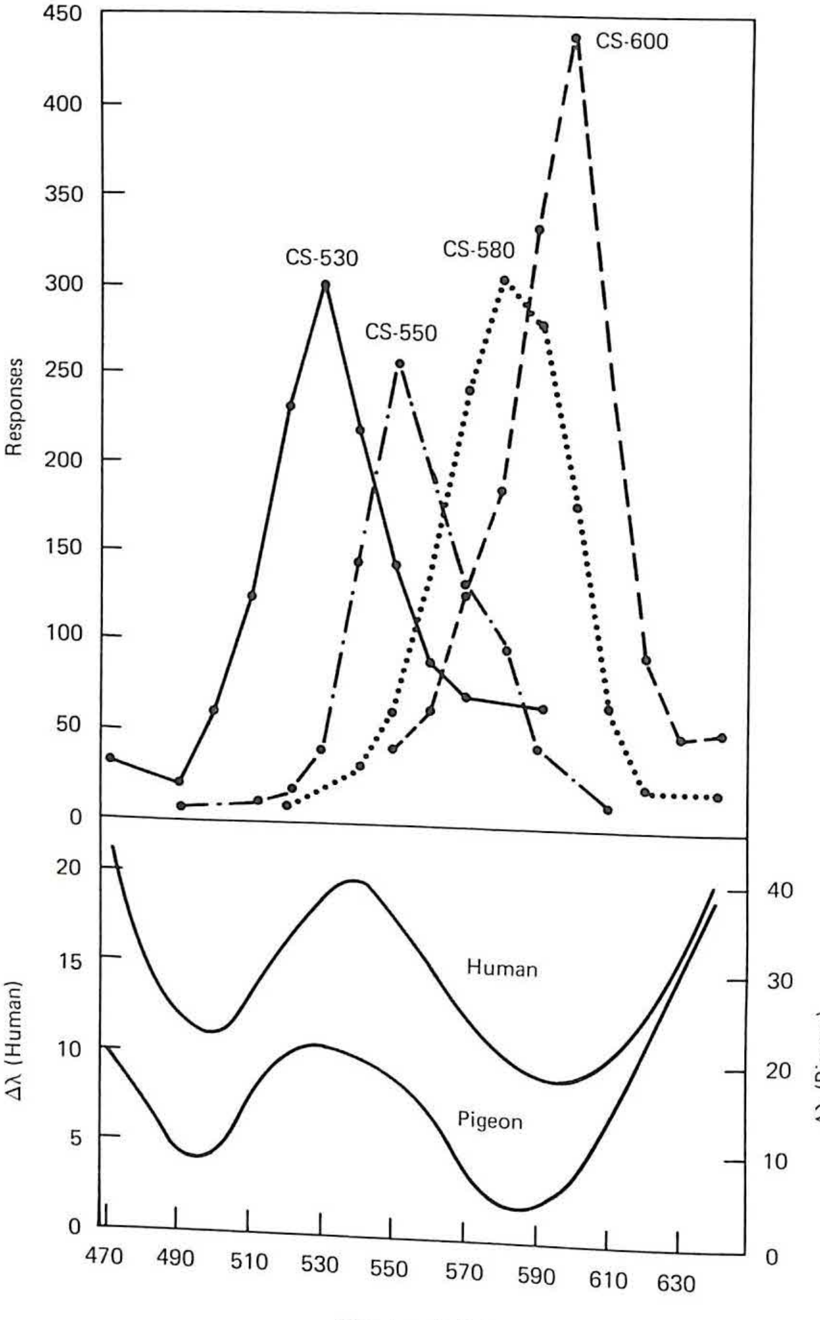

Figure 4-2. Upper: Mean generalization gradient, first test. Lower: Hue discrimination as a function of wavelength for pigeons and humans. (From N. Guttman and H. I. Kalish. Discriminability and stimulus generalization, *Journal of Experimental Psychology*, 1956 (51), 79-88. Copyright 1956 by the American Psychological Association. Reprinted by permission.)

It appears that when the 1000 hz tone was not used as a discriminative cue, there was essentially complete generation (a flat generalization gradient). The specific frequency of the tone had acquired no stimulus control over the instrumentally conditioned pecking response. Indeed, pigeons pecked as frequently when there was no tone as when there was one. From a cognitive standpoint, sound was not a relevant stimulus dimension and conceivably was not attended to by the pigeon.

Differential conditioning drew the attention of the pigeon to the tone as a relevant stimulus, and under these conditions a peaked generalization gradient was obtained. Note that in the differential conditioning used by Jenkins and Harrison, *CS*− was no tone at all rather than a tone of a different frequency. To obtain a peaked generalization gradient with respect to a stimulus dimension such as pitch, it is not necessary to use two stimuli that differ only with respect to that dimension. Simple establishment of the relevance of a stimulus such as a tone can produce generalization gradients with respect to dimensions of that stimulus, such as pitch.

Note also that except for the auditory versus visual stimulus aspect the conditions under which Jenkins and Harrison obtained flat generalization gradients were essentially equivalent to the conditions under which Guttman and Kalish obtained peaked generalization gradients with respect to wavelength. Thus, differential training within an experimental setting is not always necessary to establish control by a particular stimulus and the associated peaked generalization gradient. If the stimulus in question is already salient, as visual cues probably are to a pigeon, particularly when they are projected directly on the key being pecked, then the attributes of the salient dimension will be specifically conditioned to the response. When it is less salient, such as a background tone, it may be totally ignored.

The breadth of stimulus generalization of habits tells us, in essence, what was learned. In human beings stimulus generalization probably has even greater variation based on stimulus saliency. Stimulus saliency and the resulting generality of what is learned probably can be enormously influenced in human beings by verbal instructions. For instance, if I talk in general about the importance of being kind to people in conjunction with rewarding Ingrid for being nice to her brother, she may encode the experience in a much more general way than if I emphasize the importance of kindness among members of the same family. Parents communicate to their children what they want them to learn by both patterns of reinforcement and accompanying verbalizations.

Inhibition and Discrimination Training

Kenneth Spence formulated the theory that the *CS*+ sets up an excitatory generalization gradient around itself, while any *CS*− establishes an inhibitory generalization gradient around itself, as illustrated in Figure

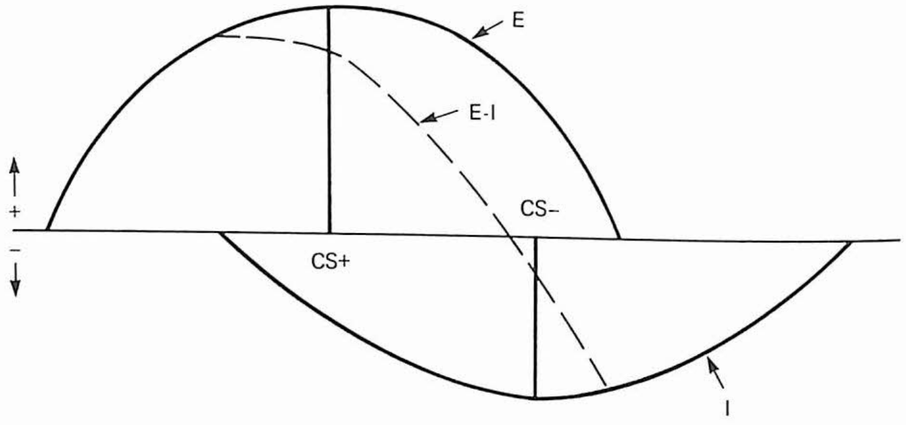

Figure 4-3. Spence's theory of the interaction of excitatory and inhibitory gradients after discrimination training of two values (*CS*+ and *CS*−) along some stimulus dimension.

4-3.[43] The shape of the excitatory and inhibitory gradients shown in the figure are hypothetical, but such gradients have interesting properties. For one thing, they predict the steepening of generalization gradients as a result of discrimination training. They also predict that the drop from the *CS* + will be relatively steeper on the side of the *CS* − than on the side away from the *CS* −. They can also predict a *peak shift*, that is, a shift in the value of the stimulus dimension that has the maximum strength of association with the *CR* away from the original *CS* + in a direction opposite to the *CS* −. Such peak shifts are obtained following discrimination training in both classical and instrumental conditioning.[44]

Many theorists have drawn the net excitatory minus inhibitory gradient as if inhibition could subtract from excitation only up to the extent of the excitation. That means that the *E* - *I* gradient in Figure 4-3 could not fall below zero. Although response rates cannot go below zero, this does not mean that the value of the theoretical variable corresponding to excitatory minus inhibitory potential does not fall below zero. Since stimuli can be established as conditioned inhibitors, it is clear that one *could* establish the *CS* − as a conditioned inhibitor, provided the *CS* − is reasonably discriminable from the *CS* +. The degree of inhibition is measured by the extent to which the *CS* − detracts from the performance of the operant in the presence of some other *CS* + when presented simultaneously with that other *CS* +. Under these conditions there ought to be negative peak shifts as well, shifts in the maximum strength of net conditioned inhibition over excitation away from the $CS-$ in the direction opposite that of the $CS+$. Thus it is possible to demonstrate that the excitatory minus inhibitory potential to perform an operant is negative under some conditions for points on a stimulus generalization gradient near a $CS-$.

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[43] K. W. Spence, "The Nature of Discrimination Learning in Animals." *Psychological Review*, 1936 (43), 427-49. K. W. Spence, "The Differential Response in Animals to Stimuli Varying Within a Single Dimension." *Psychological Review*, 1937 (44), 430-44.

[44] Mackintosh, *Animal Learning*, pp. 535-39.

Errorless Discrimination Learning

Terrace demonstrated that if a $CS-$ is introduced gradually, it is possible to establish successful discrimination learning without any erroneous responding to the $CS-$. He interrupted pigeons pecking a key illuminated with red light by blackout periods during which the birds did not peck. After pecking to the red key was well established, he gradually began to illuminate the key during the blackout period with a green light that was so dim the birds never pecked at it. Gradually the level of the green illumination of the key during the blackout was increased. When the rate of increase was sufficiently slow, the birds never pecked at the key when it was illuminated by green light ($CS-$), even when it became as bright as the red $CS+$. When discrimination training was established via this errorless procedure, the generalization gradient showed no peak shift from the $CS+$.[45]

Terrance and many other learning theorists believe that the errorless discrimination learning procedure fails to develop a gradient of inhibition about the $CS-$ because of the absence of errors. However in the absence of some inhibitory gradient around the $CS-$, it is difficult to explain nonresponding to the $CS-$ under the errorless procedure. Terrance's procedure might merely result in steeper excitatory gradients with zero excitation of the operant by the $CS-$, but the reason the procedure achieves this is far from clear. In any event, errorless discrimination training is a fascinating phenomenon in behavior control.

DISCRIMINATION LEARNING

Acquired Distinctiveness of Cues

The importance of the attentional process in discrimination learning and the capacity of animals to learn to attend to different cues was first definitively demonstrated by Lawrence in a series of experiments studying transfer between simultaneous and successive discrimination learning. An example of a *simultaneous discrimination learning* task is a T maze with one black alley and one white alley and reinforcement (for example, food) at the end of, say, the white alley. A *successive conditional discrimination learning* task also involves two alleys, one with both left and right turns painted black and one with both left and right turns painted white. The animal must learn to turn right when confronting the two black alleys and to turn left when confronting the two white alleys. Note that although the brightness (black versus white) dimension is relevant in both problems, the responses to be learned—to approach the white in the simultaneous problem and to turn right on black and turn left on white in the successive problem—are completely different. Lawrence nevertheless demonstrated significant positive transfer between such successive and simultaneous discrimination problems, compared to control groups in which animals had learned comparable prior problems with different relevant stimulus dimensions (rough versus smooth floors, chains hanging down into the alley versus no chains, wide versus narrow alleys). Since the specific *CR*s in the simultaneous and successive problems had nothing in common, the transfer must have been based on learning to attend to the relevant stimulus dimension.[46]

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[45] H. S. Terrace, "Discrimination Learning With and Without 'Errors.'" *Journal of the Experimental Analysis of Behavior*, 1963 (6), 1-27. H. S. Terrace, "Stimulus Control," in W. K. Honig (ed.), *Operant Behavior: Areas of Research and Application*. Englewood Cliffs: Prentice-Hall, 1966, pp. 271-344.

Transfer Along a Continuum

Lawrence also confirmed a finding reported by Pavlov that learning a difficult discrimination, such as two shades of gray, can be established more rapidly by prior training using a *CS*+ and *CS*− that have a more extreme difference on the same dimension, such as black versus white, than by using the light and dark gray *CS*s throughout.[47] Such a result seems inexplicable according to any single-process view, but is readily understandable if interpreted from the viewpoint that the black-white discrimination helps the animals learn which relevant stimulus dimension to attend to.

Sutherland and Mackintosh have argued that discrimination learning might be a two-stage process: (1) learning to attend to the relevant stimulus dimension (such as brightness), and (2) learning to approach the *CS*+ value of the dimension (light gray) and/or to avoid the *CS*− value (dark gray).[48] The primary reason for training on an extreme discrimination such as black-white is to draw attention to the relevant brightness dimension or to switch-in brightness analyzers and to switch-out irrelevant analyzers (in the present case left versus right position). As the organism begins to attend to the relevant stimulus dimension, learning to approach the *CS*+ and avoid the *CS*− can begin.

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[46] D. H. Lawrence, "Acquired Distinctiveness of Cues: I. Transfer Between Discriminations on the Basis of Familiarity with the Stimulus." *Journal of Experimental Psychology*, 1949 (39), 770-84. D. H. Lawrence, "Acquired Distinctiveness of Cues: II. Selective Association in a Constant Stimulus Situation." *Journal of Experimental Psychology*, 1950 (40), 175-88.

[47] D. H. Lawrence, "The Transfer of a Discrimination along a Continuum." *Journal of Comparative and Physiological Psychology*, 1952 (45), 511-16.

[48] N. S. Sutherland and N. J. Mackintosh, *Mechanisms of Animal Discrimination Learning*. New York: Academic Press, 1971.

Intradimensional Versus Extradimensional Shifts

Another phenomenon that demonstrates the importance of attending to relevant dimensions is the demonstration that greater transfer from one discrimination problem to another can be obtained when the same stimulus dimension is relevant even though the specific *CS*+ and *CS*− values are different.[49] The control condition assesses transfer with a new relevant dimension. For example, subjects might be tested in a color discrimination task in which red is the *CS*+ and yellow the *CS*−, and shape (circle versus square) is irrelevant. There is more positive transfer on this task if a prior task had color rather than shape as the relevant dimension. This superiority of intradimensional shifts over extradimensional shifts demonstrates that selective attention is not just paid to particular values of one dimension but to the entire dimension.

Fading

In a companion demonstration to errorless discrimination learning, Terrace also demonstrated that attentional control could be transferred from one stimulus dimension to another without errors. First he trained pigeons to discriminate red and green backgrounds, then he gradually superimposed horizontal lines on the red (or green) and vertical lines on the green (or red) backgrounds. The pigeons continued without error to peck to the *CS*+ and not to the *CS*−, despite the presence of the additional redundant relevant stimulus. After a number of trials in which the pigeons had pecked to the compound positive cues and not to the compound negative cues, Terrace gradually faded out the original colors. The pigeons transferred the color discrimination to the horizontal-vertical line discrimination without making any errors in the transition.[50] Obviously animals are able under proper conditions to learn something concerning a redundant relevant cue dimension, even though they have been trained to a very high level to attend to another dimension. Such fading of the relevant dimension is a particularly effective way of producing transfer of stimulus control to a new dimension.

SUMMATION

Not only can animals learn about one redundant cue while primarily attending to another cue dimension, under many circumstances they can achieve a higher rate of discrimination learning when there are two redundant relevant cues than when there is only one. Furthermore, performance on test trials is higher when both redundant relevant cues are present than when either component alone is present. Although the interpretation of such additivity involving performance with redundant stimuli is complex, the evidence suggests that rats have the capacity to attend to more than one stimulus dimension at a time both in learning and in performance.

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[49] Mackintosh, *The Psychology of Animal Learning*, pp. 597-98.

[50] H. S. Terrace, "Errorless Transfer of a Discrimination across Two Continua," *Journal of the Experimental Analysis of Behavior*, 1963 (6), 223-32.

Experiments that demonstrate *additivity of cues* in discrimination learning have sometimes been used as evidence in support of the hypothesis that summation occurs in instrumental conditioning. These findings demonstrate that learning and performance are superior in the presence of two cues (*CS*s) when both cues are present at the same time during learning. To be exactly analogous to summation experiments in classical conditioning, it would be necessary to demonstrate that two *CS*s that were separately conditioned to the same operant would have a greater probability of eliciting the operant together than either by itself. This has also been demonstrated.[51]

OVERSHADOWING

In a successive discrimination learning problem Reynolds trained two pigeons to discriminate between a white triangle on a red background that signalled that reinforcement would follow performance of the *CR*, and a white circle on a green background that signalled that nonreinforcement would follow performance of the *CR*. Following learning, he presented each component stimulus (triangle, circle, red, or green) in isolation, and was able to show that one bird had treated color as the relevant dimension and learned nothing concerning shape, while the other had treated shape as the relevant dimension and had learned nothing concerning color. In doing so he showed that overshadowing occurs in instrumental as well as in classical conditioning. In this case overshadowing was complete, although color was the more salient dimension for one bird and shape for the other.[52]

Other discrimination learning problems have not shown such complete overshadowing, but it has frequently been demonstrated that there is a negative correlation over different individuals between the stimulus control acquired by each of two elements of a compound stimulus. That is, the more an animal learned about a particular cue, the less it learned about the other.[53] It should be noted, however, that factors such as individual differences in learning ability, attentional capacity, and motivation all tend to work in the direction of producing a positive correlation, so that the failure to observe a negative correlation is of little significance.

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[51] Mackintosh, *Animal Learning*, pp. 574-79.

[52] G. S. Reynolds, "Attention in the Pigeon." *Journal of the Experimental Analysis of Behavior*, 1961 (4), 203-08.

[53] Mackintosh, *Animal Learning*, pp. 574-79.

BLOCKING

Assume that an animal has already learned a discrimination involving a particular stimulus dimension, such as brightness. Then assume that an additional cue dimension, such as tone versus not tone, is made redundantly relevant. A subsequent test involving the tone alone demonstrates that the tone acquired less discriminative control than when the compound tone and brightness training trials were not preceded by prior training involving the brightness dimension alone. The magnitude of the *blocking* effect in discrimination learning is typically substantially less than in classical conditioning, but it has been obtained in a number of studies.[54] The difference in the magnitude of the blocking effect may have little to do with the difference between classical and instrumental conditioning; more likely it results from the fact that the demonstrations of blocking in classical conditioning used aversive *US*s while the discrimination learning problems typically involved appetitive conditioning. The difference in the magnitude of the blocking effect could be attributed to the higher level of arousal or of the drive characteristic of demonstrations in aversive classical conditioning as opposed to instrumental discrimination learning, since the study by Bruner, Matter, and Papanek demonstrated that blocking is enhanced by increases in drive level.[55]

St. Claire-Smith demonstrated both overshadowing and blocking of instrumental conditioning. Rats were first trained to press a lever for food followed by classical conditioning of either a light or noise *CS* with a shock *US*. The animals were then divided into three groups, with all three groups being shocked for lever pressing rather than rewarded with food. In the blocking group, the light or noise *CS* previously paired with shock was presented coincident with each punished response. In the overshadowing group, the stimulus not paired with shock was presented simultaneously with each punished response. The control group had no external stimulus coincident with each punished response. The rate of learning the contingency between lever pressing and punishment was greatest in the control group, next in the overshadowing group and least of all in the blocking group. Thus, either the salience of a response or its ease of association to a subsequent reinforcement can be overshadowed or blocked by the presence of a more salient signal of reinforcement.[56]

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[54] *Ibid.*, pp. 582-83.

[55] J. S. Bruner, J. Matter, and M. L. Papanek, "Breadth of Learning as a Function of Drive Level and Mechanization." *Psychological Review*, 1955 (62), 1-10.

CONFIGURING

Configuring has also been obtained in instrumental conditioning, though it has been far more frequently studied within the classical conditioning paradigm.[57] In classical conditioning, the compound S_1 and S_2 serves as the *CS* to be paired with a *US*. In instrumental conditioning, the compound stimulus serves as the cue that under these conditions some response will produce reinforcement. In either case a demonstration of configuring must show that the *CR* develops in association to the compound but not to its individual constituents.

CONDITIONING AND THE SOMATIC AND AUTONOMIC NERVOUS SYSTEMS

The nervous system has been divided into many parts in our effort to understand its functioning. One fundamental division is between the central nervous system, which consists of the central integrative mechanisms within the brain and spinal cord, and the peripheral nervous system, which consists of the sensory and motor nerves that connect the brain and spinal cord to the sensory organs, muscles, and glands of the body. Another basic subdivision is between the somatic nervous system and the autonomic nervous system. The somatic nervous system is concerned with control of skeletal muscles such as those that control movements around the joints of the body (arms, legs, neck, fingers, etc.), but also with those that control movements of the tongue, eyes, throat, etc. The autonomic nervous system controls the heart, glands, and the smooth muscles in blood vessels, the stomach, intestines, and bladder. The somatic and autonomic nervous systems both contribute to the control of breathing.

The separation between the somatic and autonomic nervous system is fairly clear in the peripheral nervous system, on the basis of the parts of the body that they control and other anatomical factors. However the degree of separation of the somatic and autonomic nervous systems within the central nervous system is largely unknown. There must be a certain degree of central coordination, so the central components of the somatic and autonomic nervous systems are not completely separate. Some consider the distinction between the somatic and autonomic nervous systems to apply strictly to the peripheral nervous system, but for present purposes it seems best to include the central components of each within the definition of the somatic and autonomic nervous systems, however unknown those components may be.

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[56] R. St. Claire-Smith, "Blocking of Punishment" (unpublished paper presented at the Eastern Psychological Association Convention in Atlantic City, 1970).

[57] Razran, *Mind in Evolution*, pp. 207-21.

The somatic nervous system is generally concerned with controlling our sensory and motor interaction with the external world, while the autonomic nervous system controls the operation of strictly internal regulatory functions. Another difference is that there appears to be more conscious sensory input into and feedback from the somatic nervous system, or at least we are more aware of its functioning than we are of autonomic functioning. Finally, control of skeletal muscles by the somatic nervous system is voluntary to a far greater extent than is the control of visceral functions by the autonomic nervous system, which appears to be largely automatic.

Some years ago Miller and Konorski suggested the possibility that classical conditioning might be a property of both the autonomic and somatic nervous systems, but that only the somatic nervous system was capable of instrumental conditioning.[58] Others have transformed this rather reasonable, but unproved hypothesis into the hypothesis that the autonomic nervous system is only modifiable by classical conditioning, and the somatic nervous system only modifiable by instrumental conditioning, but there appears to be little or no support for this modification. It is clear that responses controlled by the somatic nervous system can be classically conditioned: The leg-flexion, knee jerk, and eye blink responses are all under the control of the somatic nervous system and can all be classically conditioned.[59] Furthermore, the recently discovered phenomenon of autoshaping indicates that even the pecking responses of pigeons can be conditioned using a classical procedure. Thus, there can be no doubt that the somatic nervous system possesses the capacity for classical conditioning.

It has sometimes been argued that classical conditioning is really instrumental conditioning in disguise, and that animals perform a *CR* of salivation because it makes food more enjoyable to eat, that they perform a leg-flexion *CR* because it makes the shock less painful, etc. There may be some truth to this, but the argument can be as well applied to autonomic classical conditioning as to somatic classical conditioning. Furthermore, the fact that classical conditioning of somatic responses is possible under curare, which paralyzes the muscles that perform the *CR*, indicates that the beneficial effects of performing the *CR* are in no way necessary for the occurrence of classical conditioning.

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[58] S. Miller and J. Konorski, "Sur une forme particulière des reflexes conditionnels. *Compte Rendu des seances de la Societe de Biologie*, 1928 (99), 1155-57.

[59] Mackintosh, *Animal Learning*, pp. 128-29.

Instrumental Conditioning of Autonomic *CR*s

The ability of the autonomic nervous system to be instrumentally conditioned is somewhat more in doubt. It is certainly much more difficult to instrumentally condition increases or decreases in heart rate, constriction or dilation of the blood vessels, stomach and intestinal contractions, and other visceral activity than to condition the same responses classically or to condition many skeletal motor responses instrumentally.[60] However, as Kimmel points out, there are now more than 95 studies of the instrumental conditioning of autonomic responses in human beings wtih over 90 percent success in conditioning such autonomic responses as increases and decreases in heart rate, the galvanic skin response (GSR), and constriction and dilation of blood vessels.[61] It has often been argued that such changes in autonomic responses might be mediated indirectly by the somatic nervous system through instrumental conditioning of skeletal muscle responses, changes in respiration, and the like, but the research done to date on autonomic conditioning of human beings does not appear to support such a notion of indirect mediation.

For a time it was thought that the research of Neal Miller, Leo DiCara, and their colleagues had definitively demonstrated the capacity for instrumental conditioning of a variety of autonomic responses (heart rate, vascular constriction and dilation, intestinal activity, urine formation in the kidney), independent of mediation by the somatic nervous system. Such instrumental conditioning was performed on animals under curare, which completely blocks neural control of the striped muscles controlled by the somatic nervous system but does not affect the control of smooth muscles by the autonomic nervous system.[62] However, inability to replicate many of his earlier results casts doubt on their reliability, and conclusions concerning instrumental conditioning of autonomic responses in curarized animals are now unclear.[63]

Although there is no direct evidence supporting it, it seems very likely that the changes that occur in classical and instrumental conditioning of both autonomic and somatic *CR*s occur within the central nervous system, not within the peripheral components of either the somatic or autonomic nervous systems. Hence, since the differentiation of somatic and autonomic control systems is far less clear in the central nervous system than in the peripheral nervous system, it appears to be extremely difficult to achieve any final resolution of the question concerning the capacities of the autonomic nervous system.

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[60] *Ibid.*, pp. 130-34.

[61] H. D. Kimmel, "Instrumental Conditioning of Autonomically Mediated Responses in Human Beings." *American Psychologist*, 1974 (29), 325-35.

[62] Mackintosh, *Animal Learning*, pp. 130-34.

[63] N. E. Miller and B. R. Dworkin, "Visceral Learning: Recent Difficulties with Curarized Rats and Significant Problems for Human Research," in P. A. Obrist, A. H. Black, J. Brener and L. V. DiCara (eds.), *Cardiovascular Psychophysiology: Current Issues in Response Mechanisms, Biofeedback, and Methodology*. Chicago: Aldine Press, 1974.

Practical application and biofeedback. What existing research does show is that we can achieve much more control over the functioning of the autonomic nervous system than was heretofore suspected. Although it is far too early to draw any definite conclusions concerning the therapeutic usefulness of this knowledge, a number of promising practical applications have opened up as a result of this research. For example, it may be possible through instrumental conditioning to lower blood pressure and heart rate in people with heart disease.

One of the practical techniques that has been devised for accelerating instrumental conditioning of autonomic responses such as heart rate and blood pressure is *biofeedback*. The sensory feedback from the visceral organs controlled by the autonomic nervous system does not ordinarily command our conscious attention. A number of studies have suggested that the instrumental conditioning of autonomic responses might be accelerated if subjects were supplied with auditory or visual displays of the autonomic response to be controlled, such as heart rate. For example, a subject might be given a visual display of a line on an oscilloscope whose length corresponds to the duration between successive heartbeats, and instructed to attempt to make the length of the line on the oscilloscope exceed a certain length and thus slow down heart rate. It does appear to be possible to condition autonomic responses instrumentally without biofeedback, but there is some indication that biofeedback speeds the conditioning, and in some cases instrumental conditioning of autonomic responses has not been possible without biofeedback.[64]

Biofeedback may have some promise in the control of certain somatic muscular responses as well. While we may be consciously somewhat more aware of somatic responses than of autonomic responses, there are many somatic responses to which we ordinarily pay little attention. For example, most of us are typically unaware of the contraction of our face, scalp, and neck muscles. Increases in psychological tension can produce states of extreme contraction of such muscles, often resulting in tension headaches. (Most headaches are thought to be produced by spasms caused by excessive contraction of these face, scalp, and neck muscles. Migraine headaches are produced by blood-vessel muscle spasms.) People can undoubtedly learn to monitor the state of their facial, scalp, and neck muscles and to relax them and thus reduce the frequency of tension headaches. Although it is far too early to be sure, there is some indication that biofeedback concerning the contraction of one's face, scalp, and neck muscles can play a useful role in conditioning the relaxation of these muscles.[65]

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[64] Kimmel, "Instrumental Conditioning." P. J. Lang, "Learned Control of Human Heart Rate in a Computer-Directed Environment," in Obrist, Black, Brener, and DiCara, *Cardiovascular Psychophysiology*, pp. 392-405. E. B. Blanchard, R. W. Scott, L. D. Young, and E. D. Edmundson, "Effect of Knowledge of Response on the Self-Control of Heart Rate." *Psychophysiology*, 1974 (11), 251-64.

THE RELATIONSHIP BETWEEN CLASSICAL AND INSTRUMENTAL CONDITIONING

We have noted that similar phenomena appear in both classical and instrumental conditioning. It is therefore plausible to assume that both are mediated by a common learning mechanism. There are three basic hypotheses about the relationship between classical and instrumental conditioning. One hypothesis claims that classical conditioning is instrumental conditioning, and that performance of the *CR* in anticipation of the *US* serves some function for the organism. In the case of appetitive salivary conditioning this function might be improving the taste or digestability of the food; in the case of aversive shock conditioning it might be reducing the pain of the shock. Such a theory is particularly apt for classical eyelid conditioning, because although the *CR* does not alter the world (it does not change the probability of delivery of the air puff), it does affect whether the air puff falls on the cornea of the eye or on the eyelid and thus appears to make some difference with regard to its aversiveness.

Nevertheless, it is now fairly clear that classical conditioning is not instrumental conditioning in disguise. This has been most definitively demonstrated by pairing the *CS* and *US* under conditions where performance of the *CR* is prevented by administration of curare, which blocks transmission at the neuromuscular junction. Since the *CR* cannot be performed during the pairing of the *CS* and *US*, there can be no differential reward for performance of the *CR* to mediate classical conditioning. Nevertheless, classical conditioning trials administered to animals under curare yield substantial levels of conditioning, as demonstrated by *CR*s to the *CS* once the effects of the drug have worn off. Once again, we see the substantial theoretical importance of the *learning without responding* phenomenon.

The second hypothesis is that instrumental conditioning is actually classical conditioning. Stated at such a molar behavioral level, this hypothesis does not appear logically reasonable, since instrumental conditioning requires three contingencies, while classical conditioning requires only two.

What does appear reasonable is the third hypothesis, which is that both classical and instrumental conditioning are mediated by the same underlying learning mechanism: association of contiguously activated internal representatives (nodes). This is learning by contiguity for which the classical conditioning paradigm has been considered a primary example. Nevertheless it is not correct to say that such a unified theory of classical and instrumental conditioning explains instrumental conditioning in terms of classical conditioning. Classical conditioning and instrumental conditioning are behavioral phenomena, not theoretical mechanisms. Attempts to explain one phenomenon in terms of another phenomenon are not very satisfactory as theories of either. It is explaining one mystery in terms of another. This is especially unsatisfactory with regard to classical and instrumental conditioning, because there is a logically greater complexity to instrumental conditioning than to elementary classical conditioning that must be explained in some way.

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[65] A. S. Freese, *Headaches.* New York: Schocken, 1974, pp. 156-62. D. A. Bakal. "Headache: A Biopsychological Perspective." *Psychological Bulletin,* 1975 (82), 369-82.

Two different contiguity conditioning explanations have been offered for instrumental conditioning: an *SR-K* cognitive expectancy hypothesis and an *S-R* reinforcement hypothesis. The cognitive hypothesis assumes a capacity to specify new chunk nodes for contiguously activated nodes, such as for *S-R* compounds and perhaps for entire *SR-K* propositions ("if response *R* is performed in situation *S*, outcome *K* will result"). Since the same vertical-associative contiguity conditioning appears to be required to explain configuring in classical conditioning, the cognitive expectancy hypothesis is compatible with the assumption that classical and instrumental conditioning use the same basic learning mechanisms.

According to an *S-R* reinforcement hypothesis, the presence of certain special reinforcing stimuli enables the contiguity conditioning mechanism to function (or function more effectively). This means that when an $S\text{-}R_c$ pair is followed by positive reinforcement, the horizontal association from *S* to the correct response R_c is strengthened, or at least strengthened much more than the association from *S* to an incorrect response R_i, which is not followed by reinforcement. By contiguity conditioning, the situational cues *S* should also become associated to the reinforcement, as should the correct response R_c. According to *S-R* reinforcement theory, though, it is the $S\text{-}R_c$ association that is primary in determining behavior, not the *S-K* or $R_c\text{-}K$ associations. This is especially reasonable since neither *S* alone (in the absence of the correct response R_c) nor R_c alone (in a different situation) will produce the reinforcement.

In classical conditioning the Law of Effect leads us to the reasonable assumption that *US*s are reinforcers. Therefore, contiguity conditioning of the *CS* idea node to the *US* idea node will occur, because the *US* is a reinforcer that enables the contiguity conditioning mechanism to function. Any built-in (prepared) *CR*s that are innately associated to activation of the idea node for the *US* will now be elicited by the *CS*. Thus again, in the reinforcement theory with only horizontal-associative contiguity conditioning, both classical and instrumental conditioning can be assumed to use the same basic learning mechanisms.

SUMMARY

1. Instrumental conditioning is three-contingency learning, which for higher organisms can be encoded as an *SR-K* expectancy: that response *R* in situation *S* will produce reinforcement *K*.
2. Simpler forms of instrumental conditioning may follow Thorndike's Law of Effect: what is learned is an *S-R* association, and the strong *S-R* associations are those that are frequently followed by positive reinforcement.
3. Instrumentally conditioned responses eventually extinguish when performance of the response is no longer followed by reinforcement. The greater the change in conditions from acquisition to extinction, the faster the extinction.
4. Avoidance responses are generally very difficult to extinguish by the conventional procedure: simple removal of the possibility of occurrence of the aversive stimulus. Extinction is obtained more rapidly when the aversive stimulus is presented independent of the operant.
5. Extinguished operants demonstrate spontaneous recovery after extinction training with the passage of time.
6. Instrumental conditioning is slower the greater the delay of reinforcement (feedback) following performance of the operant. The delay of reinforcement effect appears to result from the associative interference caused by performing other operants in the same stimulus context during the delay interval. When one restricts the opportunity to perform competing operants in the delay interval, or when the organism is removed from the experimental context during the delay interval, instrumental conditioning in mammals can occur with much longer reinforcement delays (up to one hour in T maze learning). This demonstrates that it is the combination of both the stimulus situation and the operant that higher organisms associate with reinforcement. Highly prepared associations (such as those between food taste and illness) can also be learned with long delays of reinforcement.
7. Intermittent reinforcement in instrumental conditioning probably retards learning somewhat, but it often produces a higher eventual rate of operant performance and invariably retards extinction.
8. Some useful practical learning principles are:
   A. Shaping: rewarding successively narrower approximations to the desired behavior.

B. Fading: transferring stimulus control to a new stimulus dimension by making it redundant in relationship to an already effective dimension, first by increasing the salience of the new dimension, then by decreasing the salience of the previously controlling relevant dimension.

C. Omission training: rewarding the nonoccurrence of an undesirable response, which makes elimination of the response more permanent than extinction (not rewarding the response).

D. Intermittent reinforcement produces learning that is more resistant to extinction than continuous (100 percent) reinforcement.

9. An instrumentally conditioned response is not a specific sequence of muscle movements but a class of movements that are functionally equivalent in that they achieve the same goal. Such functionally equivalent response classes are called *operants*.

10. Instrumental conditioning also demonstrates stimulus generalization: situations similar to that in which the operant was rewarded will also have a tendency to elicit the operant. The breadth of generalization reflects what was learned (how the learning experience was encoded). In human beings the encoding of experience is enormously influenced by language.

11. Instrumental conditioning also demonstrates stimulus discrimination. Learned operants are not performed with equal probability in all stimulus situations. Organisms are capable of discrimination learning: incorporating attributes of the stimulus situation into the memory trace, which enables them to perform operants in the presence of a *CS*+ (which signals the availability of reward) and not to perform operants in the presence of a *CS*− (which signals the unavailability of reward).

12. Higher animals appear to have the capacity for selective attention, and only stimulus dimensions that are attended to get incorporated into the memory trace. Variation from acquisition to testing of an attended stimulus dimension will produce generalization decrement; variation of unattended dimensions will not.

13. Higher animals can be *trained* to attend to certain dimensions as opposed to others, which facilitates new learning where these salient dimensions are relevant, even though other features of the task are very different.

14. The distinction between the somatic and the autonomic nervous systems is clear only for the peripheral nervous system. The memory traces established in classical and instrumental conditioning almost certainly reside in the central nervous system. In any event it is clear that autonomic responses can be both classically and instrumentally conditioned, though the mechanism is in some doubt.

15. The use of biofeedback may facilitate learning to control a variety of responses we are not normally aware of, such as heart rate, blood pressure, and muscle tension.
16. The properties of instrumental conditioning are very similar to those of classical conditioning, which suggests that the type of trace may be basically identical for both. The common properties include: acquisition, extinction, spontaneous recovery, external inhibition, disinhibition, conditioned inhibition, generalization, discrimination, summation, overshadowing, blocking, and configuring. Classical and instrumental conditioning of birds and mammals may both involve the learning of expectancies at higher levels of the nervous systems. In other animals both kinds of conditioning may be produced by the Law of Effect.
17. Both classical and instrumental conditioning can be mediated by the same underlying contiguity-conditioning mechanism. In lower species or lower levels of the nervous systems of higher species, this may be accomplished by a reinforcement mechanism that strengthens primarily the associations between contiguously activated nodes that are followed by reinforcers. Both classical and instrumental conditioning at higher cortical levels in birds and mammals may involve formation of chunk nodes representing *S-R* or *S-S* compounds or *SR-K* propositional expectancies.

5 Motivation and Learning

OBJECTIVES

1. To define the concepts of drive, satiation, reinforcement, and incentive.
2. To describe some basic properties of motivational control of behavior for three control systems, hunger, thirst, and fear, and to consider briefly some important phenomena concerning sexual motivation.
3. To present evidence that animals perform responses primarily to achieve pleasure and only as a typical secondary consequence of this to achieve a reduction of drive. (We shall see that a state of zero drive is not so pleasurable as having a drive and satisfying it.)
4. To present some facts and theories regarding the neural representation of drive, satiation, and incentive, including a discussion of the self-stimulation phenomenon (the existence of nodes in the brain whose activation produces pleasure).
5. To discuss the effects of drive level and amount of reinforcement on performance.
6. To point out that drive level and reinforcement magnitude probably have no direct effect on the speed of cognitive expectancy learning, provided the animal performs the same responses. However, drive and reinforcement magnitude can have an indirect effect on learning, by changing which responses are performed.

Motivation is concerned with goals and subgoals, and with the mechanisms by which they are obtained. According to the theory of natural selection, all or almost all the goals of an organism must be directly or indirectly concerned with survival of the species. Some goals such as sexual reproduction and care of the young, are concerned with survival of the species irrespective of individual survival. Others such as obtaining adequate nutrition, temperature regulation, control of essential bodily functions, and avoiding hostile environments, contribute to survival of the species by assisting individual survival. Still others, such as love and affiliation, contribute to both individual and species survival through the benefits of cooperation, particularly in obtaining food and in providing for defense, sexual reproduction, care of young, and the like. Organisms have many different motivational control systems, because many different goals are relevant for survival. One reason for the evolution of more complex neural and hormonal control systems may be to add new goals or to refine old goals so as to increase the chances of survival.

Motivational control systems are often classified into two basic categories: *appetitive,* concerned with achieving positive goals such as food, water, or sex, and *aversive,* concerned with avoiding negative goals such as dangerous predators, extreme heat or cold, and so forth. Obviously it is possible to consider the approach to food, water, and sex as the avoidance of hunger, thirst, and sexual deprivation; and the avoidance of predators and extreme heat or cold can be thought of as achieving a more secure environment and the optimum temperature. There are differences between appetitive and aversive motivational control systems, and differences within each class as well. Appetitive and aversive motivational systems can have both positive and negative emotional components. Hunger can be very aversive and even capable of producing extreme fear, if one does not know whether one will be able to obtain food. On the other hand sometimes danger signals evoke no fear, and can even be pleasant if one knows exactly what to do to avoid injury. Even pain can be pleasant under some conditions, and not just to masochists. Under wartime conditions many soldiers experience not pain but great joy as a consequence of receiving serious but not critical injuries, because such injuries mean they will no longer have to risk their lives in combat.

Motivational systems exist to control actions in order to achieve goals. All the goal systems we have are part of us at all times, but they are not all functioning to control behavior at the same time. One reason for this is that, at any given time, many of our goals are satisfied: we have an adequate nutritional level, an adequate salt and water balance, there are no danger signals in the environment, and so forth.

Organisms are often in states where there are conflicts between different goals. Sometimes actions to achieve different goals can be carried out simultaneously (in parallel), such as regulating temperature while breathing and preparing food for dinner. In other cases different goals require different actions by the same effectors. For example, we do not usually attempt to talk and eat at the same time, though we may do so in rapid alternation. Shifting the control of behavior from one goal to another can be very rapid. When incompatible actions are required by different motivational control systems, presumably the control system that is most strongly activated at that moment will control behavior. Partial satisfaction of that goal system may temporarily depress its degree of activation and thus allow another goal system to assume temporary control. Little is known concerning the coordination of different motivational systems.

The preceding description is reasonably accurate for motivational control systems that are concerned with internal regulation of body functioning or that are little influenced by learning. However, there appear to be two ways in which it is incomplete or inaccurate for many motivational systems in higher organisms. First, there are often fast-acting satiation mechanisms that signal the achievement of a goal, such as adequate water consumption, before the primary drive-initiating stimulus, such as the dehydration of body cells, has been restored to the *target* level. Second and more important, behavior is often primarily governed not by the desire to reach a goal state and achieve zero drive, but rather by the desire to make progress toward some positive goal. It is often the *change* of direction in relationship to the goal that is pleasurable rather than merely *being* in the goal state. Events that produce such pleasurable changes with regard to goals are termed *positive incentives*. As we shall see, many motivational control systems act primarily to maximize positive incentives rather than to achieve goal states (minimize drives).

It is useful to contrast two types of motivational control systems: the *drive-reduction* (homeostat or pure negative feedback) system and the *incentive* (mixed positive and negative feedback) system. In a drive-reduction system some discrepancy from a target (goal) level (of body temperature, for example) initiates a variety of responses (constriction or dilation of peripheral blood vessels in the skin), to reduce the discrepancy (drive). As the discrepancy is reduced, the drive-related responses decrease in magnitude or frequency.

Many internal, body-regulatory control systems are largely homeostatic (drive-reduction) in character, but the motivational control systems that involve significant interaction with the external world are incentive systems. In an incentive system, organisms work to achieve positive incentives (pleasurable subgoals), not to reduce drives. For example, eating food is an incentive (pleasurable subgoal) to an organism that has been deprived of food for some time. The hunger drive is partially activated by internal cues signalling food deprivation, but it is *increased* by external cues signalling the availability of food. Its magnitude will depend on both kinds of cues: internal food deprivation cues and external food availability cues.

This is undoubtedly functional, since the best time to be hungry is when there is the possibility of obtaining food. By having a positive (drive-increasing) rather than a negative (drive-decreasing) relationship between reinforcers (such as food or food-related cues) and drive, organisms can better match their drives to the opportunities afforded by the environment to eat, drink, build a nest, and the like.

Of course it will not do while eating food to increase the hunger drive indefinitely. Such runaway positive feedback would lead to disaster! Satiation mechanisms triggered by an accumulation of primary reinforcers (eating food) will eventually come into play and inhibit the drive (hunger).

However as we shall see, incentive systems differ in another important respect from drive-reduction systems: With incentive control systems such as hunger, it is not the achievement of a zero-drive state that animals work for; rather they work to achieve positive incentives (defined as the conjunction of a reinforcer such as eating food with an appropriate drive state such as hunger). Animals do not want to be satiated; they want to eat (which requires both hunger and food)!

Let's consider another example of a motivational control system, nest building in birds. As you probably know, most bird species build nests of such highly characteristic form that one can identify the species from examination of the nest. At the appropriate time of year, the goal of building a nest is activated in the bird's brain. The absence of a suitable nest then constitutes a discrepancy from this goal, which may help initiate a nest-building *drive*. Obtaining suitable material (sticks, straw, grasses, leaves) and arranging them properly constitute *reinforcers*. These reinforcers (potential incentives) become actual positive *incentives* when these events occur in conjunction with the nest-building drive. The presence of suitable nest-building material probably also plays a substantial role, in addition to internal bodily state, in evoking or increasing the nest-building drive. When the nest is completed, the entire drive-reinforcement-incentive nest-building goal system is suppressed (inhibited) by the nest-building *satiation* mechanism, which signals accomplishment of the goal.

This chapter is primarily concerned with analyzing the drive, satiation, reinforcement, and incentive components of some of the motivational systems that control behavior. We shall also explore whether motivation has any direct effect on learning. In Chapter 6 we shall examine the relationship between motivation and learning from the opposite direction—namely, how learning from experience affects notivation.

DRIVE

Drive is the desire to achieve a goal. Drives are at least partially initiated by discrepancies between the current state and a target (goal) state. The hunger drive is initiated by a discrepancy from an optimum state of nutrition (possibly signalled by something related to sugar metabolism or the storage of fats). Thirst is signalled by an inadequate concentration of water inside body cells. Fear is signalled by sensing a dangerous environment, which is a discrepancy from safety (security). Curiosity (the exploratory drive) is initiated by the absence of novel stimuli or the presence of boringly familiar stimuli, and so on.

In strictly behavioral experiments, hunger and thirst drives are typically manipulated by depriving an organism of food or water for varying periods of time. By and large, increasing hours of deprivation produces increasing levels of such drives, as measured by the quantities that organisms will eat or drink or the speed with which they will perform an instrumental response to obtain food or water.

Physiological manipulations of drive levels have provided considerable information concerning the physiological mechanisms of motivational control. We shall briefly consider three drives: thirst, hunger, and fear.

Thirst. At one time it was thought that the primary neural registration of thirst was from sensory neurons responding to dryness in the mouth and throat. Anyone who has slept with his or her mouth open will undoubtedly agree that extreme dryness of the mouth and throat is a sufficient condition to induce at least a limited amount of drinking. However it has been definitively established that dryness of the mouth and throat is not a necessary stimulus to induce drinking, and that under ordinary circumstances such dryness probably plays little or no role in the control of water intake.[1] What appears instead to control drinking is the concentration of water as opposed to salt in some neurons in the brain region known as the hypothalamus. Andersson demonstrated that microinjections of hypertonic salt-water solutions (water saltier than the normal goal level of the body) into a region of the hypothalamus induced drinking of water. Neal Miller reported similar effects. He also reported that an isotonic solution had no effect on drinking, and that a hypotonic solution (pure or distilled water) reduced drinking. In a subsequent experiment he found that cats would perform a learned response to obtain water as a consequence of hypertonic saline injection. Although the salt concentration of fluid in the hypothalamus probably constitutes the natural stimulus for the activation of thirst drive neurons, Andersson and McCann demonstrated that electrical stimulation of the same neurons also produces drinking. Finally, lesions in the lateral hypothalamus produce adipsia (refusal to drink) in many animals.[2]

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[1] Deutsch and Deutsch, *Physiological Psychology*, pp. 592-95. P. M. Milner, *Physiological Psychology*. New York: Holt, Rinehart, & Winston, 1970, p. 308.

[2] B. Andersson, "The Effect of Injections of Hypertonic NaCl-Solutions into Different Parts of the Hypothalamus of Goats." *Acta Physiologica Scandinavica*, 1953 (28), 188-201. N. E. Miller, "Experiments on Motivation." *Science*, 1957 (126), 1271-78. N. E. Miller, "Learning and Performance Motivated by Direct Stimulation of the Brain," in D. E. Sheer (ed.), *Electrical Stimulation of the Brain*. Austin: University of Texas Press, 1961, pp. 387-97. B. Andersson and S. M. McCann, "Drinking, Antidiuresis and Milk Ejection from Electrical Stimulation Within the Hypothalamus of the Goat." *Acta Physiologica Scandinavica*, 1955 (35), 191-201. B. Andersson and S. M. McCann, "The Effect of Hypothalamic Lesions on the Water Intake of the Dog." *Acta Physiologica Scandinavica*, 1956 (35), 312-20.

Hunger. Less is known about neural control of hunger, though once again the lateral hypothalamus has been clearly implicated, since bilateral lesions (cuts in both hemispheres of the brain) in this region produce aphagia (refusal to eat), and electrical stimulation in this area frequently induces eating. One plausible hypothesis concerning the natural stimulus for central activation of hunger, in the lateral hypothalamus or wherever, is that it is some factor closely dependent on glucose (blood sugar) metabolism, but the evidence in support of this hypothesis is not conclusive.[3]

Glucose (mainly derived from carbohydrates or fats) is but one of many important nutritional substances. Other substances are necessary to maintain adequate nutrition, such as protein, fats, vitamins, and minerals. It is possible that deficiencies of some of these substances have neural representations that induce hunger that is specific for the substance the body is deprived of. However, as we emphasized in the section on specific hungers in Chapter 2, there is good reason to believe that many specific dietary deficiencies lead to selection of nutritionally adequate diets via rejection of old diets that have become aversive because of their nutritional deficiencies. It is logically possible that only one or a few specific dietary deficiencies, such as inadequate amounts of salt, sugar, fats, or protein, are neurally registered in a manner that induces consumption. Satisfaction of other dietary deficiencies might depend not on the inducement of eating, but on the selection of the particular foods that are preferred.

Fear

Fear is an aversive drive initiated by the occurrence of an external danger signal. Many small animals exhibit innate fear reactions to the presentation of shapes resembling common predators.[4] Other stimuli can come to evoke fear as a result of the learning process, through association with innate fear-inducing stimuli or directly painful stimuli. The learned evocation of fear will be discussed in more detail in the next chapter.

Physiological psychologists have discovered centers in the brain that appear to play an important role in the encoding of fear motivation. Delgado, Roberts, and Miller obtained what appeared to be a fear reaction in cats

[3] B. K. Anand and J. R. Brobeck, "Hypothalamic Control of Food Intake in Rats and Cats." *Yale Journal of Biology and Medicine*, 1951 (24), 123-40. B. K. Anand, S. Dura, and K. Shoenberg, "Hypothalmic Control of Food Intake in Cats and Monkeys." *Journal of Physiology*, 1955 (127), 143-52. B. K. Anand, "Nervous Regulation of Food Intake." *Physiological Review*, 1961 (41), 677-708. J. M. R. Delgado and B. K. Anand, "Increase of Food Intake Induced by Electrical Stimulation of the Lateral Hypothalamus." *American Journal of Physiology*, 1953 (172), 162-68. D. Mayer, "Glucostatic Mechanism of Regulation of Food Intake." *New England Medical Journal*, 1953 (249), 13-16. J. Mayer, "Satiety and Weight Control." *American Journal of Clinical Nutrition*, 1957 (5), 184-85. Deutsch and Deutsch, *Physiological Psychology*, pp. 590-92.

[4] See Thorpe, *Learning and Instinct*, p. 69. See also Milner, p. 359.

from electrical stimulation of a particular part of the brain.[5] Other evidence indicated that it was a fear center, rather than a motor center controlling a fear-like response, since stimulation in this area of the brain could motivate the performance of a response previously learned for the avoidance of shock. Such animals also learned to escape from a compartment in which they had been so stimulated. This area of the brain would thus appear to have the more general properties characteristic of fear motivation rather than the properties characteristic of a specific response center. Stimulation of other areas of the brain can produce rage and associated aggressive responses.[6]

It is worth noting that the evocation of various motivations (emotions) by stimulation of specific sites in the brain provides evidence for Müller's doctrine of specific nerve energies for even such high-level functions. Once again it is representation by *which* neurons are activated and not by the *pattern* of activation that is important, since a variety of stimulating agents in the same region will often produce the same effect without the need to impose any exotic pattern of stimulation. If the elementary concepts represented in the brain required complex patterns of activation, we would probably not be able to evoke drives with the crude electrical stimuli that have been employed.

SATIATION

Drives represent discrepancies from goals and act to facilitate the performance of specific consummatory responses (eating, drinking, copulation) that lead to the achievement of these goals. If the success of goal-directed activities initiated by a drive were instantly registered at the drive center, then goal-directed behavior could cease because the drive stimulus itself had ceased. Reduction in drive stimuli may sometimes account in part for the termination of goal-directed behavior, but there are also satiation centers that are more rapidly activated after achieving a goal than the eventual reduction of the drive stimulus itself.

Thirst

When thirst is initiated by the natural means of depriving an animal of water, the longer animals have been deprived the more they drink (up to the capacity of the stomach).[7] Reduction in thirst drive because of water absorption from the stomach circulated by the blood stream to the thirst control centers in the hypothalamus may play some small part in the termination of drinking. Under most circumstances, though, the organism stops drinking long before enough water has passed into the blood stream to reduce the thirst drive stimulus appreciably. Hence, there must be a special thirst satiation (or drinking shut-off) mechanism.

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[5] J. M. R. Delgado, W. W. Roberts, and N. E. Miller, "Learning Motivated by Electrical Stimulation of the Brain," *American Journal of Physiology*, 1954 (179), 587-93.

[6] Deutsch and Deutsch, *Physiological Psychology*, pp. 350-66.

[7] Milner, p. 315.

A classic experiment by Bellows demonstrated for dogs that the sensory stimulation produced in the mouth and throat by drinking water activates a thirst satiation mechanism even if the water never reaches the stomach or blood stream. Bellows cut the esophagus of dogs and implanted a fistula (small tube) in the throat such that water drunk by the dogs passed through the fistula and emptied into a pan without ever reaching the stomach. Thirsty dogs drank an amount approximately proportional to their water deficit, but they would stop drinking when they had consumed approximately twice the amount normally drunk under the same degree of deprivation. If no water was put in their stomachs, they would resume drinking approximately an hour later and drink a similar amount.[8] Apparently neurons in the mouth or throat or both have the power to signal water satiation and shut off drinking, even when the natural thirst drive stimulus is still present.

Not all animals possess a water intake mouth-metering mechanism to activate a thirst satiation center in the brain. However, satiation of thirst can also be achieved by using a fistula to bypass the mouth and throat and load the stomach with water. Miller, Sampliner, and Woodrow showed that loading the stomach with water also reduces subsequent drinking, and that inhibition of drinking occurs before much water is absorbed into the blood stream.[9]

Hunger

It used to be thought that the ventromedial hypothalamus was the brain's hunger satiation center, but this hypothesis is now largely discredited. In the first place, it may not be the ventromedial hypothalamus that is so important to feeding, but the nearby ventral noradrenergic bundle.[10] Of greater psychological importance, the nature of the deficit produced by destruction of this area of the brain is not that animals cannot stop eating, but that they eat more per meal because they eat faster. Furthermore, this increase in food consumption tends to be primarily of tasty foods once such

[8] R. T. Bellows, "Time Factors in Water Drinking in Dogs." *American Journal of Physiology*, 1939 (125), 87-97.

[9] N. E. Miller, R. I. Sampliner, and P. Woodrow, "Thirst-Reducing Effects of Water by Stomach Fistula vs. Water by Mouth Measured by Both a Consummatory and an Instrumental Response. *Journal of Comparative and Physiological Psychology*, 1957 (50), 1-5.

[10] R. M. Gold, "Hypothalamic Obesity: The Myth of the Ventromedial Nucleus." *Science*, 1973 (182), 488-90.

lesioned animals have reached a new (stable but fatter) weight level. This control system appears to be related to a more long-term weight regulation system that determines the amount of food consumed by varying the appetite-generating (hunger-drive inducing) effects of food cues. Schachter has observed that many obese human beings show a similar deficit: They may actually be less hungry than normals in the absence of food cues, but they really "get into" eating when tasty food is available. Hunger in these overweight individuals appears to be more controlled by the appetite-generating effects of external food cues than by cues deriving from internal deficit (a rather reasonable hypothesis in view of their nutritional state).[11]

When cues occur that reliably signal the forthcoming availability of food, hunger drive apparently increases and continues to increase during the early stages of eating. Some brain structure affected by lesions in the area of the ventromedial nucleus acts as a partial brake on this appetite-generating system. Without this brake, animals eat faster and therefore more per meal. But this brake is apparently not the satiation (shut-off) mechanism that terminates eating altogether after a period of time. In both obese humans and ventromedially lesioned rats, eating stops after a time that is not necessarily longer than the eating time for normals. Some brain structure undoubtedly does serve as a short-term hunger satiation center, but its location is not yet known.

We know more about the more peripheral levels of the hunger satiation system. Unlike thirst, where the functional stimulus for satiation appears to originate in the mouth and/or throat, the primary functional stimulus for hunger satiation appears to derive from some consequences of food in the stomach, intestine, or blood stream (though there is apparently also some contribution to satiation derived from taste). Dogs that "sham eat" (the food passes through a fistula and never reaches the stomach) sometimes eat much more than their usual amount of food before stopping, and the amount eaten does increase reliably with degree of food deprivation. Furthermore, a number of experiments have demonstrated that direct injection of food into the stomach can produce almost immediate satiation. Such immediate satiation could not be accounted for by an increase in blood sugar level or some such factor, since digestion could hardly have proceeded to any significant extent in that period of time. Cutting the nerves from the stomach to the brain does not interfere with satiation. This suggests that there is a humoral cue that originates in the stomach and is presumably registered neurally at the satiation nucleus in the brain, which then terminates eating. Whatever this humoral stomach cue is, it is selective for nutrients, since loading the stomach with a nonnutrient saline solution has little or no effect on bar pressing to obtain food, while loading the stomach with an equivalent quantity of milk or sugar solution causes a considerable reduction in bar pressing for food.[12]

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[11] A. Sclafani and L. Kluge, "Food Motivation and Body Weight Levels in Hypothalamic Hyperphagic Rats: A Dual Lipostat Model of Hunger and Appetite." *Journal of Comparative and Physiological Psychology*, 1974 (86), 28-46. S. Schachter, "Some Extraordinary Facts about Obese Humans and Rats." *American Psychologist*, 1971 (26), 129-44.

Fear

Satiation of fear also is not just a reduction of the fear-inducing stimulus, but rather the achievement of stimuli signifying a safe environment. The relative importance of these two factors varies across species and situations. A deer running to escape a predator probably recognizes safety primarily by the absence of fear-inducing stimuli, although the length of the run might be important too. When we run into a house to escape a bee or a rabbit pops down its hole to escape a fox, it is primarily the presence of stimuli associated with a safe environment that produces a reduction in fear rather than the absence of the fear-inducing stimulus, which may still be only a few inches away, clearly visible and audible.

REINFORCEMENT

Every drive is associated with goals and subgoals that organisms try to achieve. Goal events are those in which some final state (optimum temperature, water/salt balance, blood sugar level, etc.) is reached that produces zero drive (perhaps after some delay). Subgoals are events that are relevant to achieving goals. Events that psychologists call *reinforcers* are essentially subgoals. An increase or decrease in temperature, a drink of water, a bite of food, safety signals (a dark enclosed space for a rat)—all are *primary reinforcers* (subgoals), and they are either innate or learned in a highly prepared way long before animals are tested in most psychology experiments. Other subgoals are learned by animals in experiments (getting to parts of a maze that are close to the compartment where food has been found, getting to the food cup, and the like). These learned subgoals are called *secondary reinforcers*.

Many psychologists used to define reinforcers as events that reduced drive, but we now know that this is a poor definition. For one thing, sec-

[12] R. C. Bolles, *Theory of Motivation*, 2nd ed. New York: Harper and Row, 1975, pp. 151-57. Deutsch and Deutsch, *Physiological Psychology*, pp. 606-25. W. T. James, "An Analysis of Esophageal Feeding as a Form of Operant Reinforcement in the Dog." *Psychological Reports*, 1963 (12), 31-39. M. Kohn, "Satiation of Hunger from Food Injected Directly into the Stomach Versus Food Ingested by Mouth." *Journal of Comparative and Physiological Psychology*, 1951 (44), 412-22. M. M. Berkun, M. L. Kessen, and N. E. Miller, "Hunger-Reducing Effects of Food by Mouth, Measured by a Consummatory Response." *Journal of Comparative and Physiological Psychology*, 1952 (45), 550-54. M. Smith and M. Duffy, "The Effects of Intragastric Injection of Various Substances on Subsequent Bar Pressing." *Journal of Comparative and Physiological Psychology*, 1955 (48), 387-91.

ondary reinforcers do not reduce drive. For another, as will be discussed more extensively later, in incentive motivational systems such as hunger, thirst, and sex, the immediate effect of both primary and secondary reinforcers is to *increase* drive.

The role of learning in reinforcement will be discussed in the next chapter. For present purposes we shall treat primary and secondary reinforcers as the same thing: Both are preferentially sought by organisms under the relevant drive, and both strengthen (reinforce) the tendency to perform responses that produce them.

Although I have said that reinforcers are subgoals and potential incentives (when the relevant drive is activated), my primary definition of reinforcement will be by enumeration of examples (eating food, drinking water, copulating, placing a stick in the nest, etc.). Reinforcement is itself a basic abstract concept, which we should not attempt to define in terms of more basic abstract concepts. However, the concept you already have in your mind for *subgoal* refers to the same events as the concept of *reinforcer.* Drive and satiation are also basic abstract concepts, but incentive is a derived concept because it is defined in terms of drive and reinforcement, as we shall see in the next section.

INCENTIVE

We shall define *incentive* as the combination of a drive and a relevant reinforcer. Food is a reinforcer relevant to the hunger drive, but it is not an incentive unless the animal is hungry. Satiated animals can learn the locations of relevant reinforcers, even though they may not selectively perform responses to achieve these reinforcers until they are under a relevant drive. In a latent learning experiment, for instance, an animal may learn the location of food in a maze but not perform responses to get to that location until later, when it is hungry. It is incentives that regulate performance, not reinforcers.

Such a subtle distinction between reinforcement and incentive might appear to be hairsplitting were it not for the results of a very important study by Joseph Mendelson. Mendelson made ingenious use of the fact that satiated rats can be made hungry by electrical stimulation of the hunger drive center in the lateral hypothalamus. He realized that the ability to turn the hunger drive on and off rapidly in the same way that reinforcers can be rapidly presented is a powerful tool for the investigation of important theoretical issues in the relationship between motivation, performance, and learning. In one experiment Mendelson demonstrated that satiated rats would learn a T maze to obtain food at the end of the correct arm motivated only by electrically induced hunger drive. When the brain stimulation was turned off, the rats chose randomly. Mendelson then explored

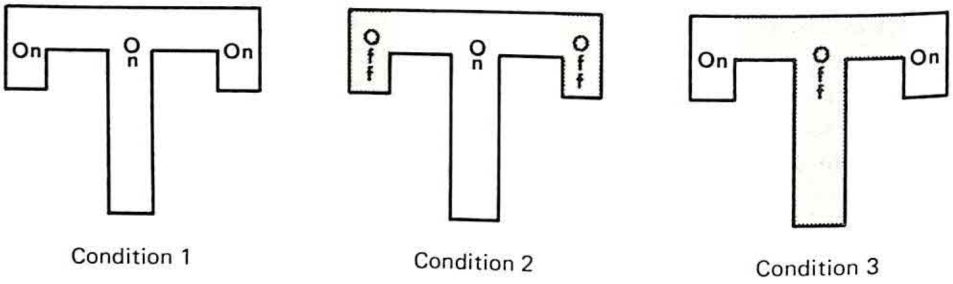

Figure 5-1. Three conditions of electrically activated hunger drive in Mendelson's experiment.

where in the T maze the rat needed to have the electrically induced hunger drive in order to learn and perform the response to obtain food: at the choice point, in the goal box or both. A diagram of the three basic conditions employed in Mendelson's experiment is shown in Figure 5-1.

If drive activates responses that lead to relevant reinforcers, then condition 2, where the drive is on at the choice point, ought to lead the rats to consistently choose the alley with food at the end. Of course in condition 2 the hunger drive is turned off when the animal reaches the goal box, and the animal, no longer hungry, does not eat. This means that there is no incentive for the animal to consistently choose the food arm in condition 2, and the result was the rats chose randomly. Any explanation of the way motivation controls performance based on the notion that drive potentiates or energizes behavior sequences that terminate in relevant reinforcement is wrong unless some account is taken of the drive condition of the organism at the time the reinforcement becomes available. Under condition 2, animals would neither learn a consistent choice nor perform the response consistently, even if they had learned it previously under condition 1, where the drive stimuli were on throughout the maze.

Where the animals *did* learn to choose the food arm of the T maze was in condition 3, where the drive was only turned on when the animal reached either goal box. (Incidentally, although the electrical stimulation was of the character that is intrinsically rewarding to the rat, this rewarding effect was balanced for both arms of the maze.) Despite the absence of a relevant drive at the choice point, the rats learned to consistently make the choice that would lead to the simultaneous inducement of drive and the satisfaction of that drive by the presence of a food reward.[13] Thus, animals will learn and perform responses to obtain incentives, defined to be the conjunction of the drive and a relevant reinforcement. The apparent conclusion to be drawn from this experiment is that control of behavior is not directed toward maintaining a driveless state, but rather toward achieving the pleasure that comes from satisfying a drive.

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[13] J. Mendelson, "Role of Hunger in T Maze Learning for Food by Rats." *Journal of Comparative and Physiological Psychology*, 1966 (62), 341-49.

In a subsequent experiment Mendelson used rats with electrodes implanted in the thirst drive region of the lateral hypothalamus to demonstrate that a nonthirsty rat would learn to press a lever delivering an electric current to make itself thirsty, if and only if there was water available to drink.[14] Thus an increase in thirst drive is not rewarding by itself, but the combination of thirst drive and water reinforcement is rewarding. In present terminology the combination of thirst and water is an incentive, and rats will perform responses to obtain incentives even in the absence of currently relevant drives, provided that the relevant drive will be present at the time the reinforcement is presented. The same sort of result was found by Coons and Cruce for rats with electrodes implanted in hunger drive areas. Such rats would rapidly stimulate themselves to induce the hunger drive when food was present, but they would stimulate themselves much less rapidly when food was not available.[15] Thus, drive induction under these circumstances appears to be a desirable event, since it allows the organism to have the pleasure of achieving an incentive. It is left to the reader to draw conclusions regarding the comparative happiness of an ascetic life dedicated to the absence of drives as compared to a life of continual striving for incentives.

It appears that even in the satisfaction of such primary maintenance drives as hunger and thirst organisms are not simple homeostats motivated by a desire to zero out all drives. Organisms seek pleasure, and in many cases there appears to be greater pleasure in the *transition* from a higher to a lower drive state than in the lower drive state itself.

Appetitive drives such as hunger, thirst, and sex do not appear to be aversive, at least when there is reasonable expectation of obtaining an incentive, but drives such as avoidance of pain and fear appear to be almost invariably aversive. It is relatively rare for an individual to seek out extreme electrical shock for the pleasure of having it turned off. Thus there appear to be negative incentives as well as positive incentives.

Negative incentives are the combination of a negative reinforcer (pain, extreme cold, a buzzing bee, disapproval) and a relevant drive (fear of physical pain, fear of loss of love). Negative reinforcers seem to play an even greater role in activating relevant aversive drives (such as fear) than positive reinforcers do in activating appetitive drives. However, internal states of mind (for example the degree of prior anxiety) play an important role in the dimension of fear evoked by external stimuli, just as the degree of food deprivation affects the extent of the hunger drive stimulated by food cues.

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[14] J. Mendelson, "Lateral Hypothalamic Stimulation in Satiated Rats: The Rewarding Effects of Self-Induced Drinking." *Science*, 1967 (157), 1077-79.

[15] E. E. Coons and J. A. F. Cruce, "Lateral Hypothalamus: Food and Current Intensity in Maintaining Self-Stimulation of Hunger." *Science*, 1968 (159), 1117-19.

With negative incentives it is again the *combination* of aversive drive and negative reinforcer that organisms seek to avoid. Negative reinforcers (a buzzing bee) are not negative incentives unless they evoke fear. Fear is not a negative incentive when one is certain that no negative reinforcer can occur (sitting in a theater watching a movie like *Jaws*). Only certain exceptional decouplings of fear and negative reinforcers point out this basic agreement with positive incentive motivation, because the primary source of fear drive is typically external negative reinforcing stimuli. Internal drive cues play a greater role in appetitive motivation, so it is more common to observe positive reinforcers that are not currently functioning as positive incentives than to observe negative reinforcers not functioning as negative incentives.

Finally, in both aversive and appetitive motivation, there are important individual differences. Highly anxious individuals have a very tight coupling between negative reinforcers and negative incentives: they *are* afraid of the mechanical shark viewed on the screen. In less anxious people, many negative reinforcers do not evoke fear and therefore are not negative incentives. As Schachter observed, obese people tend to have a tight coupling between food cues and the eliciting of the hunger drive.[16] That is, external food cues very reliably induce hunger in such individuals, and therefore food reinforcement is almost always functioning as an incentive for such people.

INTERACTION OF DRIVE AND INCENTIVE

One of the earliest definitions of incentive motivation was "a component of drive due to the expectation of reward." According to Hull and Spence this compartment of drive combined with the deprivation component to produce the total drive.[17] Guided by Mendelson's crucial experiment, we have defined all motivation as incentive motivation, noting that animals appear to work for incentives rather than to reduce drives. Several theoretical problems are solved by this position. For one thing, it is no longer a problem that incentives often increase drive in the short run. Since increased appetitive drive is pleasant, an incentive-induced increase in drive may often lead to an increase in pleasure.

For example, there is the "salted nut" phenomenon, that eating certain types of snack foods appears to increase one's motivation to eat more of the same food, such that one "can't stop eating them." It is possible that hunger drive increases as a result of stimuli closely associated to mealtime and increases still further when one begins to taste food. It is clear from the previous results that so long as the food is available such an increase in drive is pleasant, since it produces higher incentive value for the same available reinforcement. Eventually activity from the satiation center will inhibit the hunger drive, but so long as animals are working for incentives rather than zeroing out drives, it is possible and functional for incentive stimuli to increase drive level temporarily.

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[16] Schachter, "Obese Humans and Rats."

[17] C. L. Hull, *Essentials of Behavior*. New Haven: Yale University Press, 1951. Spence, *Behavior Theory*.

Another example is sex, which has produced some puzzling results for drive reduction theories. Sheffield, Wulff, and Backer selected a group of male rats that had an adequately high level of sexual motivation (the determiner was whether they would copulate with a female in heat). Those that would copulate were removed before ejaculation occurred and placed in a runway leading to a circular goal box that contained a female rat. The rats learned to run up the alley to get to the goal box, and on subsequent days, they performed this instrumental response faster and faster for the opportunity to copulate with the female, even though they were always removed before ejaculation occurred.[18] The assumption is that sexual stimulation increases the level of sexual drive and that ejaculation decreases it. Rats appear to find an increase in sexual drive pleasurable, just as under some conditions they seem to find an increase in hunger and thirst drives satisfying. There may be less difference between sex and hunger than was previously thought. Sexual stimulation is an incentive for an aroused rat, and it also acts to increase sexual drive in the short run. Likewise, food is an incentive to a hungry rat and may also act to increase hunger drive in the short run. In the long run, under ordinary conditions, sexual activity and food consumption result in the activation of satiation centers, which decreases drive levels, but this is not of immediate concern to learning and the short-term control of behavior.

SELF-STIMULATION

In 1954 Olds and Milner observed, somewhat by accident, that electrodes implanted in certain parts of the brain appeared to be pleasurable. Rats with such implants would return persistently to places where they had been stimulated and learned to press levers and perform other responses in order to receive electric shock to these "pleasure centers."[19] (In our terminology pleasure centers are simply the nodes that represent positive incentives.) This finding of reward centers in the brain is more evidence in support of the assumption of incentive representatives.

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[18] F. D. Sheffield, J. J. Wulff, and R. Backer, "Reward Value of Copulation Without Sex Drive Reduction," *Journal of Comparative and Physiological Psychology*, 1951 (44), 3-8.

[19] J. Olds and P. Milner, "Positive Reinforcement Produced by Electrical Stimulation of Septal Area and Other Regions of Rat Brain," *Journal of Comparative and Physiological Psychology*, 1954 (47), 419-27.

At about the same time Delgado, Roberts, and Miller demonstrated that other electrode placements appear to function as negative incentives. Animals will learn to perform arbitrary instrumental responses such as turning a wheel in order to avoid electrical stimulation of negative incentive representatives.[20] (It should be noted that at the low current intensities employed, electrical shock to the brain is not necessarily either painful or pleasurable, and indeed that there are many places in the brain where electrical stimulation appears to be motivationally neutral.)

For many electrode placements in the pleasure centers, animals will perform to turn them on and then to turn them off, which suggests that the sites either adapt to stimulation and thus reduce the pleasure, or they become aversive with increasing stimulus duration.[21] Since such electrical stimulation is relatively crude, activating perhaps thousands of neurons, complexities of this type are not unexpected. The positive or negative incentive effect of electrical stimulation at any point may be the net result of stimulation of many individual neurons, including some with counteracting effects.

Many electrode placements that are positively rewarding at moderate current intensities lose their rewarding effect at lower intensities, but even at the lower levels, they often induce drives. Some electrode placements in the lateral hypothalamus will produce hunger drive (inducing eating) at low levels of electrical stimulation, but at higher levels of stimulation they appear to have food-related rewarding effects.[22] And Mendelson has shown that electrodes in the "drinking area" of the lateral hypothalamus will produce self-stimulation at lower current intensities when water is available for drinking than when no water is available. When water is unavailable, a higher current intensity is required to produce self-stimulation.[23]

Many characteristics of the responses for rewarding brain stimulation have been interpreted to support Deutsch's theory that such pleasurable stimulation activates neurons that represent both drive and reinforcement (incentive). For one thing, rewarding brain stimulation appears to be so positive that animals have ignored food and bar pressed for hours at very rapid rates until they drop from exhaustion and starve to death. It has also been reported often that animals are quick to extinguish their responses to the bar once it no longer delivers electrical stimulation, and many satiated animals do not perform responses for rewarding brain stimulation when the delay of reinforcement is on a ratio schedule requiring more than 30 responses per reward (corresponding to a time of 15 seconds between rewards). Organisms working for natural reinforcers under normal drives will perform hundreds of responses per reward on ratio schedules and tolerate much longer time intervals between reinforcement. Deutsch's explanation of this difference is that the electrical stimulation activates both drive and reinforcement nodes, and for a period of several seconds gives the animal some drive to perform the next response. However, the drive effect decays over time so that after tens of seconds a satiated animal may have little or no remaining drive to perform the response. Extinction is more rapid than normal for the same reason—no drive.[24]

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[20] Delgado, Roberts, and Miller, "Learning Motivated by Electrical Stimulation."

[21] W. W. Roberts, "Both Rewarding and Punishing Effects from Stimulation of Posterior Hypothalamus of Cat with Same Electrode at Same Intensity." *Journal of Comparative and Physiological Psychology*, 1958 (51), 400-407. See discussion by Milner, pp. 390-91.

[22] D. L. Margules and J. Olds, "Identical 'Feeding' and 'Rewarding' Systems in the Lateral Hypothalamus of Rats." *Science*, 1962 (135), 374-75, B. G. Hoebel and P. Teitelbaum, "Hypothalamic Control of Feeding and Self-Stimulation." *Science*, 1962 (135), 375-77.

[23] J. Mendelson, "Self-Induced Drinking in Rats: The Qualitative Identity of Drive and Reward Systems in the Lateral Hypothalamus." *Physiology and Behavior*, 1970 (5), 925-30.

Further evidence in support of this is the difficulty animals have in learning instrumental responses for rewarding brain stimulation in discrete-trial tasks when the interval between trials is lengthened.[25] It has been repeatedly demonstrated that the negative effects of such long intertrial intervals can be overcome by the presentation of small "priming" shocks at the beginning of the next trial. Presumably such small shocks activate the drive neurons but not the reinforcement (incentive) neurons.[26]

This inability to tolerate long intertrial intervals applies primarily to satiated rats. Animals with rewarding electrode placements in hunger areas can tolerate longer intervals in performing instrumental responses to obtain rewarding brain stimulation, provided they are operating under high hunger drive.[27] In addition to providing support for Deutsch's theory, these results substantiate the claim that brain stimulation activates neurons that function as normal reinforcement or incentive centers in natural motivational control systems such as hunger and thirst.

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[24] Deutsch, *The Structural Basis of Behavior*. Deutsch and Deutsch, *Physiological Psychology*, pp. 522-45. Milner, pp. 387-92. R. E. Keesey and M. D. Goldstein, "Use of Progressive Fixed-Ratio Procedures in the Assessment of Intracranial Reinforcement." *Journal of the Experimental Analysis of Behavior*, 1968 (11), 293-301.

[25] See discussion by Deutsch and Deutsch, *Physiological Psychology*, pp. 520-22.

[26] J. Olds and P. Milner, "Positive Reinforcement Produced by Electrical Stimulation of Septal Area and Other Regions of Rat Brain." *Journal of Comparative and Physiological Psychology*, 1954 (47), 419-27. M. C. Wetzel, "Self-Stimulation After-Effects and Runway Performance in the Rat." *Journal of Comparative and Physiological Psychology*, 1963 (56), 673-78. J. A. Deutsch, D. W. Adams, and R. J. Metzner, "Choice of Intracranial Stimulation as a Function of Delay Between Stimulations and Strength of Competing Drive." *Journal of Comparative and Physiological Psychology*, 1964 (57), 241-43. C. R. Gallistel, "The Incentive of Brain Stimulation Reward." *Journal of Comparative and Physiological Psychology*, 1969 (69), 713-21. C. R. Gallistel, "Failure of Pretrial Stimulation to Affect Reward Electrode Preference." *Journal of Comparative and Physiological Psychology*, 1969 (69), 722-29.

[27] M. Sidman, J. V. Brady, J. J. Boren, D. G. Conrad and A. Schulman, "Reward Schedules and Behavior Maintained by Intracranial Self-Stimulation." *Science*, 1955 (122), 830-31. J. Olds, "Runway and Maze Behavior Controlled by Basomedial Forebrain Stimulation in the Rat." *Journal of Comparative and Physiological Psychology*, 1956 (49), 507-12. Deutsch and Deutsch, *Physiological Psychology*, pp. 527-32.

Despite this impressive support, Deutsch's theory appears to require some modification in light of Mendelson's demonstration that animals will learn and perform responses in order to obtain incentives even though they are not under a relevant drive at the time they make a choice. Furthermore, some tests of the hypothesis that drive persists after rewarding brain stimulation have been negative. Cox, Kakolewski, and Valenstein and Stella and Gallistel report that immediately after brain stimulation rats were inhibited from eating, when the effect of the stimulation itself was to induce eating. Stellar and Gallistel found that the pretrial priming stimulation presumed by Deutsch and Gallistel to initiate drive actually inhibited rats running to a food reward.[28] Other research is necessary to rule out other drives, but food was the most likely candidate for the drive effect of the priming shock in this case. In any event Mendelson's study makes it likely (1) that rats learn and perform instrumental responses for rewarding brain stimulation because they anticipate receiving a positive incentive, and (2) that it is not necessary for rats to be operating under any particular drive when they are performing the response.

Why animals sometimes have more difficulty in tolerating long intertrial intervals for rewarding brain stimulation than for natural rewards is something of a mystery without Deutsch's drive explanation. However, it has been argued that rewarding brain stimulation is more analogous to a consummatory response than to an arbitrary instrumental response, and that consummatory responses extinguish more quickly than instrumental responses with either natural reward or brain stimulation. Pliskoff, Wright, and Hawkins used a two-bar Skinner box constructed such that pressing the first bar on an interval schedule led to the introduction of the second bar to be pressed in order to receive a rewarding brain shock. Because the consummatory (brain shock) bar was always rewarded, schedules of responding on the instrumental bar of as long as eight minutes on a fixed-interval schedule were possible. The performances were not always the same as those of rats bar pressing for conventional reward at the longer intervals, but a reasonably high level of performance was obtained under this procedure even when the intervals between shocks were so long that according to Deutsch's theory the motivation to perform the response should have been eliminated. The reverse side of the coin is that rats will quit licking a dipper for sugar water very quickly once the supply of sugar water is cut off, just as they will stop performing a response for brain stimulation very quickly once the electricity is turned off.[29]

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[28] V. C. Cox, J. W. Kakolewski and E. S. Valenstein, "Inhibition of Eating and Drinking Following Hypothalamic Stimulation in the Rat." *Journal of Comparative and Physiological Psychology*, 1969 (68), 530-35. C. R. Gallistel, "Motivation as Central Organizing Process: The Psychophysical Approach to Its Functional and Neurophysiological Analysis." *Nebraska Symposium on Motivation*, 1974 (22), pp. 183-250. E. Stellar and C. R. Gallistel, Discussed in Gallistel, "Motivation as Central Organizing Process."

As Milner has noted, there is considerable individual variation in brain stimulation studies that is presumably dependent upon different electrode placements. With some placements animals will tolerate long intertrial intervals and quickly learn to perform responses for brain stimulation even when the interval between brain stimulations is as long as a day.[30] Other animals appear not so much to lack drive to perform responses as to find the entire situation so aversive that they respond by freezing at the end of the box farthest from the lever with their backs to it. When so many neurons are activated in such a complex and unnatural way by electrical stimulation, it is not surprising that the aftereffects of "rewarding" brain stimulation are aversive in some (but not all) cases.

The complexities of research on rewarding brain stimulation should not obscure the significance of the basic findings. There appear to be specific neurons in the brain, which for consistency we shall term positive and negative incentive nodes, that represent pleasure and displeasure. Animals will learn and perform responses in order to activate positive incentive nodes and to prevent the activation of negative incentive nodes. Different neurons appear to function as incentives for different drives such that naturally induced hunger will enhance the rate of self-stimulation at certain sites and increasing levels of sex hormones will enhance the self-stimulation rate at other sites. Stimulation at these latter sites sometimes leads to seminal emission.[31] In general, the anatomical locus of reward centers is approximately the same as the anatomical locus of the relevant drive centers, with the same electrode able to produce drive at low levels and reward at higher levels. Thus there can be little doubt that self-stimulation studies are dealing with the activation—albeit in a rather unnatural way—of reward or incentive neurons in natural motivational systems.

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[29] S. S. Pliskoff, J. E. Wright and T. D. Hawkins, "Brain Stimulation as a Reinforcer: Intermittent Schedules." *Journal of the Experimental Analysis of Behavior,* 1965 (8), 75-88. W. E. Gibson, L. D. Reid, M. Sakai, and P. D. Porter, "Intracranial Reinforcement Compared with Sugar-Water Reinforcement." *Science,* 1965 (148), 1357-59.

[30] Milner, p. 390-92.

[31] J. V. Brady, J. J. Boren, D. Conrad, and M. Sidman, "The Effect of Food and Water Deprivation upon Intracranial Self-Stimulation." *Journal of Comparative and Physiological Psychology,* 1957 (50), 134-37. J. Olds, "Effects of Hunger and Male Sex Hormone on Self-Stimulation of the Brain." *Journal of Comparative and Physiological Psychology,* 1958 (51), 320-24. L. J. Herberg, "Seminal Ejaculation Following Postively Reinforcing Electrical Stimulation of the Rat Hypothalamus." *Journal of Comparative and Physiological Psychology,* 1963 (56), 679-85.

THE EFFECTS OF MOTIVATION ON LEARNING AND PERFORMANCE

Amount of Reinforcement

The greater the amount of reinforcement, the higher the level of performance of conditioned responses. For example, the time it takes hungry rats to run down an alley from a start box to obtain food in a goal box decreases from trial to trial as they learn there is food in the goal box. The greater the amount of food in the goal box, the faster the rats run. However, for such cognitive expectancy learning (in birds and mammals), the effects of amount of reinforcement appear to be entirely on performance rather than on learning.[32] That is, rats appear to learn equally quickly at either low or high levels of reinforcement that there is food in the goal box, but performance, as measured by running speed, depends both on the degree of learning and on motivation to perform the response. The classic experiments of Crespi and Zeaman demonstrated that when the amount of reinforcement was shifted during the course of learning, from low to high or from high to low for half the rats in each reinforcement condition, running speed shifted immediately to the level appropriate to the current level of reinforcement. (There was even some overshoot, or contrast effect.) If low reinforcement had produced a lower level of learning, performance for the group shifted from low to high should have been below that of the high group for a considerable number of trials following the shift. Instead their performance increased abruptly to the same level as the high group, which demonstrates that the degree of learning obtained in the trials preceding the shift must have been approximately the same for both low and high reinforcement conditions, but that the performance measure (running speed) depends on both the degree of learning and the incentive for performing the conditioned response. When drive level is controlled, greater reward means a greater incentive to perform a response, but not necessarily greater learning.[33]

Drive Level

The same sort of conclusion applies to the effects of drive level on performance and cognitive expectancy learning. That is, drive level appears to affect performance but does not necessarily affect learning, so long as the organisms perform the necessary responses to expose themselves to the contingency to be learned and provided their attention is not distracted as a result of control by a different drive. Hillman, Hunter, and Kimble demonstrated that when level of water deprivation was switched from two to 22 hours or from 22 hours to two hours during the course of learning, running speed in an alley to obtain water shifted almost immediately to the level appropriate for the group that had been run continuously under the same drive condition.[34] Latent learning experiments described in Chapters 4 and 7 point to the same conclusion: regardless of motivation level organisms can learn what leads to what.

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[32] Kimble, *Conditioning and Learning*, pp. 122-23.

[33] L. Crespi, "Quantitative Variation of Incentive and Performance in the White Rat." *American Journal of Psychology*, 1942 (55), 467-517. D. Zeaman, "Response Latency as a Function of the Amount of Reinforcement." *Journal of Experimental Psychology*, 1949 (39), 466-83.

Motivation only affects learning indirectly, by controlling performance and attention. The least successful experiments in demonstrating latent learning are those in which animals that are running a maze are under the control of a different drive—for example, the thirst drive to obtain water—at the time that they are systematically exposed to the presence of food in a particular location. In one experiment, rats had to stumble over food pellets in order to get to water, but later, when they were hungry, they demonstrated very little learning of the location of food.[35] An animal that was completely satiated with respect to all relevant drives, including exploratory drives (by way of prior exposure to a maze), would probably learn very little concerning the location of food that was placed in a certain part of the maze, because it would be so unmotivated that it would not perform the necessary exploratory behavior to expose itself to the location of the food. However if the animal were moved through the maze on a cart, latent learning could probably be demonstrated (provided it was awake).

On the basis of present evidence, it appears reasonable to conclude that motivation has no direct effect on degree of learning but that its indirect effects, through performance and attention, can be considerable. For example, if you did not have some degree of motivation to read a book, you would not open it and could hardly learn what was in it.

SUMMARY

1. A *drive* is a desire to achieve a goal that is at least partially initiated by a difference between the current state of an organism and the goal state with respect to some dimension such as cellular dehydration for thirst, sugar metabolism or fat level for hunger, an awareness of danger signals for fear.

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[34] Kimble, *Conditioning and Learning*, pp. 411-16. A. K. Bartoshuk, "Motivation," in Kling and Riggs, *Experimental Psychology*, pp. 830-131. B. Hillman, W. S. Hunter, and G. A. Kimble, "The Effect of Drive Level on the Maze Performance of the White Rat." *Journal of Comparative and Physiological Psychology*, 1953 (46), 87-89.

[35] Kimble, *Conditioning and Learing*, pp. 226-32. G. R. Grice, "An Experimental Test of the Expectation Theory of Learning." *Journal of Comparative and Physiological Psychology*, 1948 (41), 137-43.

2. *Satiation* with respect to some drive is the achievement of the goal state for that motivational system. The peripheral sensory stimulus for satiation of thirst appears to result from neural taste signals originating from the mouth as a result of drinking. The peripheral sensory stimuli for satiation of hunger may sometimes arise partly from the taste of food in the mouth, but the primary cause of satiation of hunger is probably some humoral cue arising from the presence of food in the stomach.
3. *Reinforcers* are subgoals that have to do with achieving the goal state and eventually reducing drive. Primary reinforcers are either innate or learned in a highly prepared way. Secondary reinforcers are learned in a more cognitive and probably less prepared way. Primary reinforcers eventually result in reduction of drive, but typically do not do so immediately and may often increase drive in the short run. Secondary reinforcers by themselves do not reduce drive.
4. An *incentive* is the combination of a drive and a related reinforcer.
5. The regulation of internal bodily functions such as temperature may be largely by means of drive-reduction (homeostatic) motivational control systems in which the drive (for example a discrepancy from optimum temperature) produces a response (vasoconstriction) that reduces the discrepancy from the goal.
6. Motivational systems that involve substantial interaction with the external world (such as hunger, thirst, sex, and fear) use incentive control systems. Both internal (state of the organism) cues and external reinforcer (incentive) cues contribute to total drive. Animals perform previously learned responses and learn new associations to achieve positive incentives and avoid negative incentives, not to achieve zero drive. This is a locally positive feedback system: Drives turn reinforcers into incentives that the organism works to achieve, the incentives maintain or increase drive. When enough primary reinforcement has been achieved (enough water has been drunk), special satiation mechanisms come into play to inhibit the motivational system (thirst) that was controlling behavior.
7. There appear to be specific centers (nodes) in the brain that represent drives and (positive and negative) incentives. Activation of a positive incentive node—a pleasure center—serves as a reward that increases the tendency to perform the response that produced stimulation of the pleasure center. Activation of a negative incentive node acts as a punishment that reduces the tendency to perform the response that produced stimulation of the negative incentive node.
8. Incentive nodes are related to specific drives such that some positive incentive nodes are more rewarding if the animal is hungry and other nodes are more rewarding if the animal is sexually aroused.

9. The amounts of reinforcement and drive level affect performance but have no direct effect on how much is learned in cognitive expectancy learning by higher organisms. However by affecting the stimuli that are attended to and the responses that are performed, motivation can indirectly affect what is learned—or whether anything is learned at all.

6 Learned Motivation: Acquired Drives and Reinforcers

OBJECTIVES

1. To describe how neutral stimuli acquire the capacity to elicit fear through association with aversive stimuli.
2. To discuss the role of fear in escape, avoidance, and punishment tasks.
3. To present the cognitive theory that organisms perform responses to avoid negative incentives rather than to reduce fear drive, as an explanation of the difficulty of extinguishing avoidance responses with conventional methods.
4. To point out that punishment does not weaken associations, but instead establishes an additional association between the punished stimulus-response compound and a negative incentive.
5. To describe the concepts of innate and learned safety signals, which indicate freedom from danger.
6. To describe the capacity of learned reinforcers to facilitate learning and retard extinction.
7. To describe the factors that influence the acquisition and extinction of the secondary reinforcement value of a stimulus.
8. To provide support for the cognitive interpretation of secondary reinforcers as subgoals that are useful in predicting the occurrence of primary reinforcers.
9. To describe the failure of attempts to condition appetitive drives such as hunger or thirst to neutral stimuli by pairing these stimuli with states of hunger or thirst.
10. To discuss learned helplessness and its possible relationship to depression.

Most of the goals toward which human beings strive have been heavily influenced by prior learning and are far from being innate incentives. The desires to own one's own home, to have a new car, to graduate from college, to get a good grade on a test, or to be elected president of a club are not innate reinforcers. Even the good tastes of foods had to be acquired as positive reinforcers at one time, though this learning process is highly prepared (as we discussed in Chapter 2)—that is, strongly constrained by genetic factors. No one knows the set of truly innate or highly prepared primary rienforcers; they are probably a relatively small set in comparison to the vast number of secondary reinforcers that have become associated through learning with primary reinforcers.

The subject of acquired motivation can be organized on two binary dimensions: appetitive versus aversive motivation and learned drives versus learned reinforcers. First, we shall discuss acquired fear, the principal learned aversive drive that has been studied. Second, we shall discuss learned safety, the principal learned positive reinforcement in the aversive sphere. Third, we shall discuss secondary (learned) reinforcement in the appetitive sphere. Fourth, we shall discuss the mixed evidence regarding the existence of learned appetitive drives. Finally we shall consider learned helplessness and depression which is a learned emotional reaction wtih profound behavioral consequences, that can result from experiencing uncontrollable aversive events.

LEARNED FEAR

Conditioned Fear

A classic study by Watson and Rayner demonstrated that a one-year-old child named Albert developed a fear of a previously neutral stimulus object (the sight of a rat) as a result of a classical conditioning procedure that paired the sight of a rat (*CS*) with a loud, unpleasant sound (*US*), which evoked an unconditioned emotional response (*UR*) including crying and other apparent signs of fear.[1] Following the conditioning of fear (*CR*) to the white rat, the fear generalized to other animals such as a caterpillar, and to furry objects such as a ball of cotton. Not all subsequent studies have been successful in producing conditioned fear, and Valentine demonstrated the role that preparedness can play by showing that fears are more easily conditioned to some stimuli, in particular furry objects, than to other objects, such as a pair of opera glasses.[2]

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[1] J. B. Watson and R. Rayner, "Conditioned Emotional Reactions." *Journal of Experimental Psychology*, 1920 (3), 1-14.

[2] C. W. Valentine, "The Innate Bases of Fear." *Journal of Genetics and Psychology*, 1930 (37), 394-419.

Escape

An aversive stimulus such as an electric shock generally produces vigorous attempts to escape from the situation. A device that has frequently been used to study escape learning is the shuttle box, which is a chamber divided into two compartments separated by a hurdle or a door. The floors of one or both compartments can typically be electrified to produce a painful shock to the feet of an animal placed in the compartment. An animal shocked in one compartment will run and jump about until it finally jumps over the hurdle and escapes into the "safe" compartment. In one-way escape experiments, the two compartments are distinctively different (one might be black and the other white), and the animal is only shocked in one of the two compartments. This becomes the dangerous compartment, and the other becomes the safe compartment. In two-way escape experiments, the two compartments are identical, and the organism learns that the compartment in which it is initially placed is dangerous and that it must get into the second compartment in order to escape shock. There may be no logical ambiguity concerning which compartment is safe and which is dangerous in the two-way task, but there are obviously more cues available to distinguish the safe and dangerous compartments in the one-way task.

Neal Miller's classic experiment demonstrated that a previously neutral stimulus can acquire fear drive properties that motivate the learning of a new response so as to escape from the newly acquired danger stimulus. The basic task involved a shuttle box with a dangerous white compartment, a safe black compartment and a door between the two compartments that was initially unlocked. The rat was first shocked in the white compartment and learned to escape through the door into the black compartment. This procedure established the white compartment as a dangerous fear-inducing stimulus. The door was then locked, but it could be opened by turning a wheel inside the white compartment. Miller demonstrated that many rats learned the completely new wheel-turning response to escape from the white compartment even when no shock was ever presented again in the white compartment.[3]

Brown and Jacobs also demonstrated the capacity of fear to motivate the learning of an escape response: jumping over a hurdle into the safe compartment. In this experiment the rats were first shocked in the dangerous compartment without any opportunity to escape. Once that compartment was established as dangerous, the rats learned to jump the hurdle to escape from the dangerous compartment, even though no further shock was presented.[4]

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[3] N. E. Miller, "Studies of Fear as an Acquirable Drive." *Journal of Experimental Psychology*, 1948 (38), 89-101.

[4] J. S. Brown and A. Jacobs, "The Role of Fear in the Motivation and Acquisition of Responses." *Journal of Experimental Psychology*, 1949 (39), 747-59.

The learning of new responses in these studies occurred even though shocks were no longer presented in the dangerous compartment. Such results suggest that a neutral stimulus can acquire the capacity to elicit a fear drive, and that animals will learn new responses in order to reduce the fear drive. However, the results are just as easily interpreted to mean that the previously neutral stimulus has become an acquired negative incentive from which animals will learn to escape.

Avoidance

It is but a small step from Miller's escape-from-danger paradigm to an avoidance paradigm. In an avoidance paradigm, Solomon and Wynne placed dogs in one compartment of a shuttle box, then gave a warning signal (*CS*), followed ten seconds later by a shock (*US*). The dogs could avoid the shock by jumping from one compartment to another in the ten seconds before the shock came on. For the first few trials the dogs experienced the shock and eventually managed to escape. Once they first jumped into the other compartment in less than ten seconds and thus avoided the shock completely, they continued in later trials to jump before the shock came on and never again experienced shock. Furthermore, the jumping latencies continued to decrease for many trials after the last shock.[5]

According to Mowrer and Miller, avoidance learning is a two-stage process. First, the animal conditions an emotional fear drive to the warning *CS*. Then if a response is effective in escaping from the *CS*, it is reinforced by reduction of the fear drive.[6]

Some experiments have investigated escape and avoidance learning where a different response had to be made to the *CS* in order to avoid the shock rather than the response which had to be made once the shock came on to escape from shock. Such learning is possible under some conditions, but not surprisingly is considerably more difficult than when the escape and avoidance responses are identical or highly similar.[7] Preparedness also plays an important role. Bolles has emphasized that animals have a repertory of innate responses to painful or fear-inducing stimuli, such as escaping or occasionally crouching.[8] If the escape or avoidance response to be learned is relatively high on the innate hierarchy of responses to aversive stimuli, it will be rapidly learned, but responses that are rather low in the hierarchy will be learned only with great difficulty or not at all.

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[5] R. L. Solomon and L. C. Wynne, "Traumatic Avoidance Learning: Acquisition in Normal Dogs." *Psychological Monographs*, 1953 (67), No. 354.

[6] Miller, "Fear as an Acquirable Drive." D. H. Mowrer, "On the Dual Nature of Learning: A Reinterpretation of 'Conditioning' and 'Problem-Solving.' " *Harvard Educational Review*, 1947 (17), 102-48.

[7] O. H. Mowrer and R. R. Lamoreaux, "Fear as an Intervening Variable in Avoidance Conditioning." *Journal of Comparative and Physiological Psychology*, 1946 (39), 29-50.

[8] R. C. Bolles, "The Avoidance Learning Problem," in G. H. Bower (ed.), *The Psychology of Learning and Motivation*, Vol. 6. New York: Academic Press, 1972, pp. 97-145.

As we noted in Chapter 4, conventional extinction of avoidance responses is extremely slow, and sometimes avoidance responses do not extinguish at all. From a cognitive standpoint, the failure to extinguish is not surprising. If the *CS* is followed in ten seconds by electric shock but animals have learned an avoidance response that they always perform in less than ten seconds, then the animals never have the opportunity to learn that the shock no longer comes on. For the two-factor fear theory, the failure to extinguish has been a problem. Since the *CS* is no longer paired with shock, the fear associated with the *CS* should extinguish and reduce the motivation to perform the avoidance response. This should result in increases in latency, giving the animal an opportunity to learn that the previously dangerous compartment is no longer dangerous.

Under many conditions, this does not appear to happen. What does happen is that the latency of performing the avoidance *CR* to the *CS* decreases to some asymptotically low level and stays there, sometimes indefinitely—at least beyond the patience of most experimenters. Solomon, Kamin, and Wynne demonstrated that when extremely painful electric shocks were used, dogs would continue to perform the avoidance response with a latency that was maintained at an asymptotically low level for hundreds of trials. The avoidance response was essentially not extinguishable unless special therapeutic methods were used, such as restraining the dog in the dangerous compartment to expose it to the fact that the compartment was no longer dangerous.[9]

The extreme difficulty in extinguishing fear appears to be consistent with the difficulty that human beings often have in extinguishing anxiety reactions even when, from a rational point of view, they are clearly counterproductive in most of one's current life situations. For example, many people clearly recognize that they have an irrational level of social anxiety that prevents their having comfortable relations with other people. Meaningful reductions in social anxiety often require special methods of treatments over periods of months or years. Of course the social environment of a human being is rarely so benign as to constitute a 100 percent extinction condition for social anxiety, and partial reinforcement greatly lengthens the time of extinction, as we saw in Chapter 4.

Some human fears can be extremely persistent, but there is reason to believe that after many trials of avoidance conditioning animals no longer have much fear; nevertheless they maintain a high level of avoidance responding even though they appear calm and controlled, almost indifferent to the situation. Measurement of autonomic indicators of fear of the *CS*, such as increased heart rate, indicate that the fear extinguishes; still the animals perform avoidance responses at a high level.[10] Also, Kamin, Brimer, and Black showed that the ability of the *CS* to suppress other operant behavior declines after successful avoidance responding.[11] Thus, while fear drive may be an important component in the initial learning of avoidance responses, it does not appear to be necessary for its maintenance.

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[9] R. L. Solomon, L. J. Kamin, and L. C. Wynne, "Traumatic Avoidance Learning: The Outcomes of Several Extinction Procedures with Dogs." *Journal of Abnormal and Social Psychology*, 1953 (48), 291-302.

Such anomalies are easily explained by the theory that animals work not to reduce drives but to achieve positive incentives and avoid negative incentives. From this standpoint, an animal does not need to be under an aversive fear drive in order to perform an avoidance response. All that is necessary is that the organism anticipate a negative incentive if it remains in the dangerous compartment, and this anticipation is sufficient to motivate the performance of an avoidance response.[12]

Also, from this more cognitive perspective, as we noted in Chapter 4, the conditions for extinction of the association between the danger *CS* and the negative incentive are absent, because the animal does not remain in the dangerous compartment for the length of time it takes for the negative incentive to occur. This is true because *CS* onset and the dangerous compartment do not constitute the complete danger *CS*, which in this case is remaining in the dangerous compartment longer than ten seconds after the onset of the *CS*. If the animal never remains in the compartment long enough, it never experiences the *CS* and therefore has no opportunity to learn that the *US* does not follow the *CS*. That is, the necessary conditions for extinction are not present, and so there is no reason to expect much extinction unless by forcing the animal to remain in the dangerous compartment. When this is done, by means of a restraint or immobilization by curare, extinction of avoidance *CR*s occurs.[13]

Fear Summation

Rescorla and LoLordo used a special procedure designed by Sidman to train dogs to avoid an electric shock. The Sidman avoidance procedure schedules a shock every ten seconds unless the dog jumps the hurdle from one compartment of a shuttle box to the other. If the dog does jump, the next shock is postponed for 30 seconds. Such a schedule leads dogs to avoid shock indefinitely by maintaining a steady level of instrumental jumping responses. After a stable rate of responding was established, Rescorla and LoLordo arranged the box so no jumping was possible. Then they presented many classical conditioning trials consisting of a five-second 1200 hertz tone (*CS*+) followed by unavoidable shock through the grid floor of the box. On other trials a 400 hertz tone (*CS*−) came on for five seconds and was not followed by shock. Under such conditions the *CS*+ came to signal the arrival of shock, while the *CS*− became a conditioned inhibitor of shock. Days of this type of classical conditioning alternated with days in the Sidman avoidance procedure for a total of five classical conditioning days and seven avoidance days. Following this preliminary training, dogs were tested under the Sidman avoidance procedure, but at random times the *CS*+ or the *CS*− was turned on to determine if such stimuli would have any effects on the rate of performing the avoidance response of hurdle jumping. The significant effects were that the rate of performing the avoidance response tripled immediately after the *CS*+ was presented and fell almost to zero immediately following the *CS*−. After the *CS*− went off, the response rate gradually increased to baseline level over a period of about half a minute, but after the *CS*+ went off, a more interesting pattern was displayed: Within about five to ten seconds after the *CS*+ termination, response rate fell abruptly below baseline level. On these test trials, no shock followed either the *CS*+ or the *CS*−, so the effect on response rate could not be due to the presentation or termination of shock itself.[14] An illustration of how performance of an avoidance *CR* can be affected by presentation of an added danger (*CS*+) or a safety signal (*CS*−) is shown in Figure 6-1.

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[10] R. L. Solomon and L. C. Wynne, "Traumatic Avoidance Learning: The Principles of Anxiety Conservation and Partial Irreversibility." *Psychological Review*, 1954 (61), 353-85.

[11] L. J. Kamin, C. J. Brimer, and A. H. Black, "Conditioned Suppression as a Monitor of Fear of the *CS* in the Course of Avoidance Training." *Journal of Comparative and Physiological Psychology*, 1963 (56), 497-501.

[12] F. D. Irwin, *Intentional Behavior and Motivation: A Cognitive Theory*. Philadelphia: Lippincott, 1971. M. E. P. Seligman and J. C. Johnston, "A Cognitive Theory of Avoidance Learning," in McGuigan and Lumsden, *Contemporary Approaches*.

[13] Solomon, Kamin, and Wynne, "Traumatic Avoidance Learning."

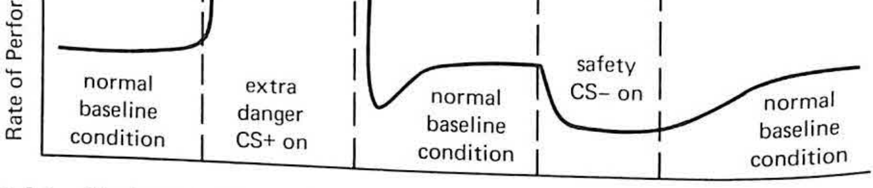

Figure 6-1. The hypothetical results of a fear summation experiment where a baseline level of performance of an avoidance *CR* is increased by presentation of an extra danger signal (*CS*+) and decreased by presentation of a safety signal (*CS*−).

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[14] R. A. Rescorla and V. M. LoLordo, "Inhibition of Avoidance Behavior." *Journal of Comparative and Physiological Psychology*, 1965 (59), 406-12.

The results cannot be accounted for in terms of summation of association to the particular avoidance response, since no response to the *CS*+ in the classical conditioning procedure affected the probability of occurrence of the shock. However, the results can be explained under the assumption that the *CS*+ or *CS*− summed with the danger cues in the avoidance situation to produce a summation or a reduction of fear. According to a more cognitive interpretation, the summation was in the expectation of danger, with the *CS*− functioning as a safety signal indicating a period of time free from shock.

The results of the Rescorla and LoLordo study can be interpreted in at least two different ways. Solomon and Corbit theorize that emotional states are organized into mutually inhibitory pairs such that the presence of an increase in fear would be followed by a period of relaxed euphoria and a gradual return to baseline, as occurred in this case. Interestingly enough, the same theory predicts that a state of euphoria is the second stage of a fear reaction and therefore would exhibit a simple return to baseline without an overreaction in the opposite direction, which is exactly what happened here.[15] Another reasonable interpretation is that the dogs had learned that the shock terminated shortly following the *CS*+ and thus the period of several seconds following the *CS*+ became a learned safety signal that generalized to the condition when the shock did not follow the *CS*+.

Punishment

Presentation of a conditioned fear stimulus will suppress an ongoing response, but a generally more effective and specific way to suppress responses is to punish their occurrence. Thorndike at first believed that the effects of punishment were symmetrical to those of reward—that reward increases the tendency to make a response and punishment weakens the same tendency. However, it is now clear that the dynamics of punishment are as follows: Punishment suppresses a response by establishing a competing (*SR-N*) association between the stimulus-response compound and a negative incentive (*N*, the punishing stimulus) rather than by weakening the previously established *SR-K* association between the stimulus-response compound and a positive incentive (*K*). For example, Skinner established a lever-pressing response using a fixed-interval schedule of reinforcement. At the beginning of extinction, half the rats were punished and half were not. The punished animals completely suppressed responding for a period of time, but they eventually emitted the same total number of responses during extinction as the rats that had not been punished.[16]

Estes found that punishment did produce a slight reduction in the number of responses emitted in extinction of the appetitive lever-pressing response (when food was no longer produced by lever pressing), but that it never did completely eliminate the need for extinction. Here again the temporary suppression produced by punishment was followed in all cases by a resumption of responding on the lever, and it took many unreinforced responses for the rats to learn that pressing the lever no longer produced food. A subsequent experiment by Boe and Church used a more intense electric shock as punishment and obtained more permanent effects of punishment in reducing the number of responses during extinction.[17]

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[15] R. L. Solomon and J. D. Corbit, "An Opponent-Process Theory of Motivation: I. Temporal Dynamics of Affect." *Psychological Review*, 1973 (81), 119-45.

[16] B. F. Skinner, *The Behavior of Organisms*. Englewood Cliffs: Prentice-Hall, 1938.

So there is nothing necessarily transient about conditioning to negative incentives. However, the fact that at some levels of punishment one can obtain immediate suppression followed by recovery and then extinction of the appetitive response seems plausibly explained by the notion that the organism has learned two associations: between the stimulus-response compound and the positive incentive on the one hand, and between the stimulus-response compound and the negative incentive on the other. The associations to both the positive and negative incentives can be acquired and extinguished independently.

One of the most paradoxical findings in the animal-conditioning literature comes from an attempt to decrease the performance of an avoidance response by reversing the contingencies and punishing performance of the avoidance response but not punishing failure to perform the avoidance response. For example, a dog that has been conditioned to jump a hurdle from one compartment to another to avoid shock is no longer punished for remaining in the previously dangerous compartment, but *is* punished, by electric shock, for jumping into what had previously been the safe compartment. The results were not that the dogs were induced to stop performing the avoidance response, but rather that they jumped faster and more vigorously into the shock than they would under the conventional extinction procedure alone.[18] A variety of other studies using aversive stimuli have also produced such vicious-circle behavior.[19] The reason for this is not clear, but one plausible hypothesis is that the punishment maintains a high level of fear in the situation and the animals continue to make the response that they have previously learned to make in the presence of such fear.

There may be some analogues of this experimental finding in human experience. If one wishes to change the behavior of an extremely anxious individual, punishment of inappropriate behavior is probably not a wise procedure. If, as is likely, the inappropriate responses were performed because of the anxiety, punishing these responses will increase the anxiety and may actually increase inappropriate behavior.

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[17] W. K. Estes, "An Experimental Study of Punishment." *Psychological Monographs*, 1944 (57), No. 263. E. E. Boe and R. M. Church, "Permanent Effects of Punishment During Extinction." *Journal of Comparative and Physiological Psychology*, 1967 (63), 486-92.

[18] Solomon, Kamin, and Wynne, "Traumatic Avoidance Learning."

[19] R. M. Church, "The Varied Effects of Punishment on Behavior." *Psychological Review*, 1963 (70), 369-402.

LEARNED SAFETY

The reduction of an aversive stimulus such as pain or fear is a positive incentive, but the presence of some stimuli appear to positively signal safety and security as well. Some stimuli appear to be innate safety signals. For example, nocturnal animals appear to feel safer in dark places, and burrowing animals undoubtedly feel safer huddled in small holes in the ground.

In addition to innate safety signals, previously neutral stimuli can also come to serve as learned safety signals, if they are associated with the absence of aversive stimuli. In the experiment of Rescorla and LoLordo that we referred to previously, the *CS*− that had been associated with the absence of shock came to serve as a learned safety signal that reduced the performance of a fear-motivated response.[20] The standard habituation procedure can be interpreted as conversion of a novel stimulus that initially elicits mild fear into a safety signal, but there is no definitive evidence that habituated stimuli ever became more than neutralized danger signals.

The hypothesis that animals actively learn that something is safe has been extended by Rozin and Kalat to include what happens when animals learn that a novel food is safe to eat. Their hypothesis was that after an animal ingests a novel food, the association between the food and safety is strengthened so long as the animal remains healthy, and the longer the time following ingestion in which the animal does not become sick, the stronger the association between the food and safety becomes.[21] They also demonstrated that the longer the time after consumption of a new food, or the more frequently a rat has consumed the food without resulting illness, the more resistent the rat is to forming a learned aversion to the food on some subsequent occasion when eating the food is followed by poisoning.[22] This probably explains why most of our food aversions are developed during early childhood, and why we are not continually forming new aversions (except in rare instances for an infrequently eaten food such as sauce Bernaise). Once we have learned that a food is safe, this learning apparently protects us from forming an aversion to it if on some later occasion we become sick shortly after eating it (unless this happens repeatedly). It is primarily only to relatively novel food that we develop an aversion, provided we become sick after eating it.

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[20] Rescorla and LoLordo, "Inhibition of Avoidance Behavior."

[21] P. Rozin and J. W. Kalat, "Specific Hungers and Poison Avoidance as Adaptive Specializations of Learning." *Psychological Review*, 1971 (78), 459-86.

[22] J. W. Kalat and P. Rozin, " 'Learned Safety' as a Mechanism in Long-Delay Taste-Aversion Learning in Rats." *Journal of Comparative and Physiological Psychology*, 1973 (83), 198-207.

SECONDARY REINFORCEMENT

Food for a hungry animal and water for a thirsty animal are primary reinforcers—positive incentives for which an animal will learn and perform responses independent of any association of food or water to other stimuli. Such primary reinforcers are often considered innate or established by highly prepared learning.

For humans and other higher organisms, most reinforcers are not primary, but are established by ordinary learning through association with primary reinforcers. For example, money has little or no primary reward value, but obviously it has considerable secondary reward value for humans, because it can be exchanged for a variety of primary reinforcers. People will work for money as a subgoal, even if some time elapses between when they obtain the money and when they exchange it for a primary reinforcer; but they will do so only so long as money retains the capacity to be converted into primary reinforcers. If a government collapses, and everyone quits accepting its money as a medium of exchange, the money loses its value as a secondary reinforcer, except insofar as there is some hope that it might regain its functional value. However, both human experience and laboratory experiments have established that the reinforcement value of a secondary reinforcer almost completely extinguishes if the secondary reinforcer is no longer associated with primary reinforcement. In fact, perhaps the best criterion for distinguishing between a primary and a secondary reinforcer is whether the reinforcement value can be behaviorally extinguished.

The Properties of Secondary Reinforcers

Secondary reinforcers have a number of properties that have been demonstrated in laboratory experiments. First, the presence of a secondary reinforcer can prolong extinction of an instrumental *CR* previously followed by primary reinforcement.[23] For example, animals that have learned to run down an alley to obtain food from a cup in the goal box will maintain the conditioned running response at a higher lever during extinction, when the food is no longer present in the goal box, if the food cup itself remains in the goal box during extinction.

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[23] R. Bugelski, "Extinction with and without Subgoal Reinforcement." *Journal of Comparative Psychology*, 1938 (26), 131-34. R. C. Miles, "The Relative Effectiveness of Secondary Reinforcers Throughout Deprivation and Habit-Strength Parameters." *Journal of Comparative and Physiological Psychology*, 1956 (49), 126-30.

Second, secondary reinforcers can be used to reinforce the learning of new responses. Grindley showed that hungry chicks learned to run down an alley reinforced by the mere sight of food in the goal box. Saltzman first trained rats to run down an alley to obtain food in a white goal box, then placed the rats in a modified T maze, with a white goal box at the end of one arm and a black box at the end of the other arm. The rats then learned to make a turning response in the T maze reinforced only by the presence of the secondary reinforcer, the white goal box. (Of course a control group that had been fed in a black goal box learned to go to the black goal box.) Eventually, however, such performances extinguish, presumably as the association between the secondary reinforcer and the primary reinforcer extinguishes. Grindley and Saltzman found that the secondary reinforcing value of the sight of unavailable food and of the previously positive goal box extinguished after a few trials when they were not paired with primary reinforcement. Such extinction was indicated by slower running times in Grindley's alley and a return to random choices in Saltzman's T maze.[24]

Third, secondary reinforcement is also presumed to play an important role in the original learning process. For one thing, much goal-directed behavior consists of chains of responses, each of which achieves some subgoal that eventually results in primary reinforcement. Such subgoals achieved are considered secondary reinforcers, and animals will learn new responses to obtain subgoals that have previously been relevant for the achievement of some primary goal. Under some circumstances such secondary reinforcers (learned subgoals) can help to bridge delay of reinforcement intervals between critical choice responses and their consequences. For example, in Chapter 4 we discussed how if a delay is introduced between making a choice response and obtaining a reward in a T maze by retaining animals in a delay box, the rate of learning the correct responses is retarded. However, learning with long delays can be greatly facilitated if the delay boxes or other stimuli associated with the incorrect turns are made distinctively different in appearance, such as when one delay box is black and the other white. Under such conditions animals can learn to associate a particular goal box with primary reinforcement (which makes that goal box a secondary reinforcer), and they can then learn that one turn leads to this secondarily reinforcing delay box but that the other does not.[25]

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[24] G. C. Grindley, "Experiments on the Influence of Amount of Reward on Learning in Young Chickens." *British Journal of Psychology*, 1929 (20), 173-80. I. J. Saltzman, "Maze Learning in the Absence of Primary Reinforcement: A Study of Secondary Reinforcement." *Journal of Comparative and Physiological Psychology*, 1949 (42), 161-73.

[25] C. C. Perkins, Jr., "The Relation of Secondary Reward to Gradients of Reinforcement." *Journal of Experimental Psychology*, 1947 (37), 377-92. G. R. Grice, "The Relation of Secondary Reinforcement to Delayed Reward in Visual Discrimination Learning." *Journal of Experimental Psychology*, 1948 (38), 1-16.

Under conditions of ordinary T maze learning, the more distinctive the difference in the stimuli characterizing the two alternative arms, the more rapid the learning.[26] Perhaps the distinctive stimuli of the correct arm become secondary reinforcers through their association with the reward in the goal box. Conversely, the more one equates the secondary reinforcers associated with the two alternatives, such as by placing food cups at the end of *both* arms, the more one retards the rate of learning.[27] Secondary reinforcement thus appears to contribute substantially to the simple behavior chain involved in learning a T maze.

Human affairs are of course filled with examples of behavior chains, each consisting of a series of responses (operants) that achieve subgoals (secondary reinforcers). For example, when I come home hungry for dinner at the end of the day, my first subgoal is to select what I want to eat, say lamb chops, baked potato, and asparagus. My next subgoal is to turn on the oven, wash the potato (and compulsively inspect for rot spots), and put it in the oven. Next, I set the timer for 35 minutes to tell me when to start the meat and vegetables. When the timer rings, I put some salted water in a sauce pan on the stove to boil, wash and cut the asparagus, put it in the pan, season the lamb chops, and so on. Some time later I get to eat! This example is trivially short compared to many human behavior chains. Clearly, secondary reinforcers play a basic role in all human behavior.

The Acquisition of Secondary Reinforcers

The strength of a secondary reinforcer is often measured either by its ability to retard extinction or by its ability to reinforce new learning. As with any type of associative learning, the strength of a secondary reinforcer is increased by increasing the number of pairings of the secondary reinforcer-to-be with primary reinforcement. There appears to be an optimum delay interval between the secondary reinforcer-to-be and the primary reinforcer. Bersh paired a light with the presentation of food in a Skinner box at intervals of 0, 0.5, 1, 2, 4, or 10 seconds. After a number of trials to establish the light as a secondary reinforcer, a bar was introduced into the box, and pressing the bar produced the light. The number of bar presses during the first ten minutes of the test provided a measure of the strength of the secondary reinforcement value acquired by the light as a function of the time interval between the secondary and primary reinforcers during training. This function showed a maximum for a forward conditioning interval (secondary reinforcer before primary reinforcer) of approximately half a second, with less secondary reinforcement value being acquired by the simultaneous pairing conditions and declines for longer forward conditioning intervals. An experiment by Shoenfeld, Antonitis, and Bersh obtained no secondary reinforcement value for a light that was presented one second after food was presented. Thus, backward conditioning was ineffective.[28]

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[26] Mackintosh, *Animal Learning*, pp. 576-79.

[27] D. Ehrenfreund, "Effect of a Secondary Reinforcing Agent in Black-White Discrimination," *Journal of Comparative and Physiological Psychology*, 1949 (42), 1-5. Kimble, *Conditioning and Learning*, pp. 192-94.

As with other forms of conditioning, intermittent pairing of a reinforcer with a primary reinforcer produces much slower extinction of the secondary reinforcing properties of the previous stimulus. Fox and King compared extinction of secondary reinforcement value for a group of animals that had experienced a buzzer (secondary reinforcement) followed by food on all its occurrences with a group in which the buzzer was followed by food on only half of its occurrences. The intermittently reinforced buzzer retained its secondary reinforcement value longer than the continually reinforced buzzer, measured by the number of bar presses subsequently made to produce the buzzer.[29]

Another acquisition variable that affects the strength of a secondary reinforcer is the degree to which the stimulus is attended to during presentation of the primary reinforcer.[30] A neutral stimulus that is not attended to during presentation of a primary reinforcer acquires little strength as a secondary reinforcer. All other things being equal, a transient stimulus (one that goes on and off) such as a tone burst or flash of light will attract more attention than a continuously sounding tone or a continuous light and so is a stronger secondary reinforcer. Of course continuously available stimuli are often less predictive of the primary reinforcer than a transient stimulus whose onset is immediately prior to primary reinforcement.

The informative or predictive value of a stimulus for signalling the occurrence of a primary reinforcer is a major factor in a stimulus acquiring secondary reinforcement value. Cues associated with both reward and nonreward, such as background lights and tones continually present in a Skinner box, acquire little or no secondary reinforcement value compared to cues differently associated only with reward.[31] Even a cue consistently associated with primary reinforcement may develop little secondary reinforcement value if it is completely redundant, in the sense that some other cue has already predicted the occurrence of primary reinforcement or if another cue is a more reliable predictor. Egger and Miller taught rats to press a lever to obtain food, then they removed the lever and presented two neutral stimuli, S_1 and S_2, in that order followed by food reinforcement. Under these conditions S_2, the redundant predictor of food, acquired much less secondary reinforcement value than S_1, as demonstrated by the ability of each to maintain lever pressing in a subsequent extinction test, where pressing the lever produced S_1 or S_2 but no food.

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[28] P. J. Bersh, "The Influence of Two Variables upon the Establishment of a Secondary Reinforcer for Operant Responses." *Journal of Experimental Psychology*, 1951 (41), 62-73. W. N. Schoenfeld, J. J. Antonitis, and P. J. Bersh, "A Preliminary Study of Training Conditions Necessary for Secondary Reinforcement." *Journal of Experimental Psychology*, 1950 (40), 40-45.

[29] R. E. Fox and R. A. King, "The Effects of Reinforcement Scheduling on the Strength of a Secondary Reinforcer." *Journal of Comparative and Physiological Psychology*, 1961 (54), 266-69.

[30] Mackintosh, *Animal Learning*, pp. 246-48.

[31] C. B. Ferster, "The Effect on Extinction Responding of Stimuli Continuously Present During Conditioning." *Journal of Experimental Psychology*, 1951 (42), 443-49.

Another group of rats received trials in which S_1 and S_2 were consistently followed by food, but they also received trials in which S_1 was presented and not followed by food. For these rats S_1 was not so reliable a predictor of food as S_2, even though S_1 still always occurred prior to S_2. Under these conditions S_2 the more reliable predictor, acquired slightly greater secondary reinforcement value than S_1. The results indicated that both the reliability of a cue and its temporal priority in a sequence of predictive cues affect the secondary reinforcement value it acquires.[32]

The *amount* of primary reinforcement associated with the secondary reinforcer-to-be usually has little or no effect on secondary reinforcement value, which provides support for a more cognitive interpretation of secondary reinforcement.[33] In particular, a stimulus may serve as a secondary reinforcer not because it can be a positive incentive in and of itself (under proper drive), but rather because it has been *predictive* of primary reinforcement. In many situations the capacity of a secondary reinforcer to prolong extinction or to promote new learning may be only secondarily affected by the strength of the primary reinforcer's incentive value.

More convincing support of the cognitive interpretation of secondary reinforcement is the fact that the drive level of the organism at the time the secondary reinforcer is established appears to have little or no effect on the strength of the secondary reinforcer. Brown gave two groups of rats 60 pairings of light and buzzer with a food pellet. One group had high hunger drive, the other group had low drive. Control groups at each drive level received an equal number of presentations of the light and buzzer, but they were not closely paired with food. When the groups were subdivided for testing, Brown found that the secondary reinforcement value acquired by the light and buzzer was unaffected by whether rats had acquired the secondary reinforcer under conditions of high or low hunger drive. (Of course, it was affected by whether the stimuli were paired with food.)[34]

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[32] M. D. Egger and N. E. Miller, "Secondary Reinforcement in Rats as a Function of Information Value and Reliability of the Stimulus." *Journal of Experimental Psychology*, 1962 (64), 97-104. M. D. Egger and N. E. Miller, "When Is a Reward Reinforcing? An Experimental Study of the Information Hypothesis." *Journal of Comparative and Physiological Psychology*, 1963 (56), 132-37.

[33] C. O. Hopkins, "Effectiveness of Secondary Reinforcing Stimuli as a Function of the Quantity and Quality of Food Reinforcement." *Journal of Experimental Psychology*, 1955 (50), 339-42. W. F. Reynolds, W. B. Pavlik, and E. Goldstein, "Secondary Reinforcement Effects as a Function of Reward Magnitude Training Methods." *Psychological Reports*, 1964 (15), 7-10.

Secondary reinforcers can appear to serve as incentives under appropriate drive conditions to the extent that they activate the expectation of primary reinforcers. The real incentive might be the combination of the expected primary reinforcer and the relevant drive, but from a behavioral standpoint there may be little difference between primary and secondary reinforcers so long as there is no extinction of the association between the secondary reinforcer and its primary reinforcer(s).

LEARNED APPETITIVE DRIVES

As we have previously discussed, a neutral stimulus that is consistently paired with an aversive stimulus that already evokes fear comes to evoke a fear drive. In view of this, it is reasonable to ask whether there is an appetitive analogue of conditioned fear—that is, whether it is possible for a neutral stimulus that is consistently paired with activation of an appetitive drive such as hunger to become a *CS* evoking the hunger drive. A number of experiments have been performed on this topic with the following basic form: An animal is kept in a distinctive environment during periods of extreme hunger, and later it is determined whether the animal eats more in that environment than in another environment not paired with extreme hunger. A few of these experiments have reported somewhat positive outcomes, but the overwhelming majority have obtained negative outcomes.[35] It appears that neutral stimuli do not acquire the ability to evoke a hunger drive as a result of occurring contiguously with naturally evoked hunger.

One possible reason for this is the more gradual onset of natural hunger drive and the continuous presence of the environmental cues, as opposed to the rapid onset characteristic of most conditioned and innate fear-inducing stimuli. However when thirst is rapidly evoked by saline injections or electric stimulation of the thirst centers in the brain, there is still no evidence that neutral stimuli can become secondary appetitive drives.[36]

Actually, as discussed in Chapter 5, conditioned activation of the hunger drive may well occur, but in a way that is exactly opposite from the procedure employed in the experiments on conditioned hunger drive: Instead of associating a previously neutral stimulus to the *absence* of food and eating, one associates the stimulus with the *presence* of food and eating. To the extent that the positive incentive of eating food has the short-term, direct effect of increasing hunger drive, a stimulus that comes to be a secondary reinforcer, predictive of eating food, should also indirectly increase hunger drive. Closely related to this hypothesis is Schachter's theory that for many obese individuals activation of the hunger drive is largely under the control of external stimuli associated with eating, such as the sight of food. Schachter also theorizes that activation of the hunger drive for many nonobese individuals is much less affected by external stimuli and more under the control of internal deprivation cues, so there may be considerable individual differences in the magnitude of this effect.[37]

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[34] J. L. Brown, "The Effect of Drive on Learning with Secondary Reinforcement." *Journal of Comparative and Physiological Psychology*, 1956 (49), 254-60.

[35] J. S. Brown and I. E. Farber, "Secondary Motivational Systems." *Annual Review of Psychology*, 1968 (19), 99-134.

[36] I. Greenberg, "The Acquisition of a Thirst Drive (unpublished doctoral dissertation, University of Pennsylvania), cited in J. F. Hall, *Psychology of Motivation*, Philadelphia: Lippincott, 1961. B. Anderson and S. Larsson, "An Attempt to Condition Hypothalamic Polydipsia." *Acta Physiologica Scandinavica*, 1956 (36), 377-82.

LEARNED HELPLESSNESS AND DEPRESSION

When I was a child my parents told me repeatedly that there was no limit to what I could accomplish if I worked hard enough, and my parents recognized and rewarded all my accomplishments, so that I fully believed this fantastic assertion until I was well into my twenties. I later discovered that this was something of an exaggeration, but the optimism and self-confidence generated by it have to a large extent innoculated me against the depressing effects of minor adversities. Up to a point, at least, failure and abuse only induce me to work harder, and I remain certain of ultimate success. I only hope I can give my children the same type of headstart in life that my parents gave me.

Most children are not so lucky. The most important features of a small child's environment are largely beyond his or her control. If that environment is largely negative—that is, if the child has few successes and many frustrations and disappointments no matter what he or she does—is it any wonder such a child grows up to be a pessimistic and depressed adult? If a child's small accomplishments receive no recognition or praise, if indeed the child's attempts to gain attention are rebuffed by parents who are wrapped up in their own problems, it would not be surprising if the child learned that his actions make no difference. Such a child may develop a basic belief in his helplessness to control the significant events in life. Seligman speculates that one important cause of depression in adults is the belief that one is helpless to control the important events of life.[38]

A number of studies support the conclusion that uncontrollable aversive events tend to cause animals to give up and passively accept subsequent aversive environments, even when escape is possible.[39] For example, dogs initially given 64 unsignalled and inescapable traumatic shocks were subsequently drastically more impaired in escape learning in a shuttle box than a control group not previously given inescapable shock. In fact, almost all the dogs that had previously received inescapable shock quickly gave up responding at all and passively accepted the shock. Even on the few trials when they did jump over the barrier, they appeared not to learn anything from the experience, because on the next trial they would go back to passively taking the shock. This phenomenon is called *learned helplessness.*

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[37] S. Schachter, "Some Extraordinary Facts about Obese Humans and Rats." *American Psychologist*, 1971 (26), 129-44.

[38] M. E. P. Seligman, "Depression and Learned Helplessness," in R. J. Friedman and M. M. Katz (eds.), *The Psychology of Depression: Contemporary Theory and Research*. New York: Halsted Press, 1974. M. E. P. Seligman, "Fall into Helplessness." *Psychology Today*, June 1973, pp. 43-48.

Seligman and Maier demonstrated that dogs can be immunized to a substantial extent against such learned helplessness by prior experience with escapable shock in a shuttle box. If the dogs have had an opportunity to learn an escape and avoidance response, subsequent exposure to inescapable shock does not retard escape and avoidance when the dogs are returned to the shuttle box.[40]

Therapy is also possible for learned helplessness. Seligman, Maier, and Green forcibly pulled "helpless" dogs from one side of the shuttle box to the other in order to terminate the shock. They reported that after 20 to 50 forcible exposures to the escape-avoidance contingency, all dogs began to respond successfully.[41]

Stress

Some years ago a great deal of attention was given to a study of "executive monkeys" who could avoid shock by making an active response at a certain rate according to a Sidman avoidance schedule. It was reported that these executive monkeys developed stomach ulcers and died as a result of the stress of the decision-making process, but that control animals, which received the same number and duration of shocks as the executive monkeys but had no control over the shocks, did not develop ulcers.[42] It is now clear that the reverse is the case, that it is uncontrollable aversive experiences rather than controllable aversive experiences that produce stress and a higher tendency to develop stomach ulcers. Uncontrollable but predictable shocks produce less stress than uncontrollable and unpredictable shock.[43] These results are very reasonable. Controllability and predictability allow one to relax during the periods that one can be confident of the absence of aversive events, but unpredictable, uncontrollable aversive events offer no opportunity to relax. Whatever causes stress in human executives, it is not the decision-making process and the prediction and control of events. Rather, it is more likely that it is the frequent uncontrollability and unpredictability of events among human executives who expect to achieve greater prediction and control than is possible that produces the stress and the stomach ulcers.

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[39] M. E. P. Seligman, S. F. Maier, and R. L. Solomon, "Unpredictable and Uncontrollable Aversive Events," in F. R. Brush (ed.), *Aversive Conditioning and Learning.* New York: Academic Press, 1971, pp. 347-400.

[40] M. E. P. Seligman and S. F. Maier, "Failure to Escape Traumatic Shock." *Journal of Experimental Psychology,* 1967 (74), 1-9.

[41] M. E. P. Seligman, S. F. Maier, and J. Green, "The Alleviation of Learned Helplessness in the Dog." *Journal of Abnormal Psychology,* 1968 (73), 256-62.

[42] J. V. Brady, R. W. Porter, D. G. Conrad, and J. W. Mason, "Avoidance Behavior and the Development of Gastroduodenal Ulcers." *Journal of the Experimental Analysis of Behavior,* 1958 (1), 69-72.

SUMMARY

1. Neutral stimuli acquire the capacity to elicit fear (the anticipation of a negative incentive) by association with aversive events. Such fear can summate when two fear-inducing stimuli are present.
2. Animals can learn to perform responses motivated by the desire to escape or avoid a fear-inducing stimulus.
3. Extinction of avoidance responses is slow because animals always perform the avoidance response and therefore never learn that failure to perform the avoidance response is no longer followed by an aversive stimulus. When animals are restrained from making the avoidance response, extinction is obtained.
4. It is not the reduction of fear that reinforces and maintains performance of the avoidance response, but the anticipation of a primary negative incentive (the aversive stimulus) if the response is not performed.
5. Animals learn to stop performing a previously rewarded response (*R*) in some situation (*S*) not because the positive *SR-K* expectancy has been weakened by punishment, but rather because a new *SR-N* (*N* = the punishing stimulus) association has been established between the *S-R* compound and a negative incentive.
6. There are innate safety signals, such as darkness for nocturnal animals, and it is possible for a previously neutral or even a fear-inducing stimulus to become a safety signal by association with the absence of aversive events.
7. Secondary (learned) reinforcers, which are subgoals that predict primary reinforcers, play an important role in learning a sequence of several responses to achieve a primary reinforcer. They also can retard extinction of previously learned responses and reinforce the learning of new responses.

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[43] Seligman, Maier, and Solomon, "Unpredictable and Uncontrollable Aversive Events."

8. The acquisition of secondary reinforcement value for a stimulus follows the usual laws of associative learning on the interpretation that the secondary reinforcement value of a stimulus comes by virtue of a learned association to some primary reinforcer. Thus, greater secondary reinforcement value is acquired by a stimulus: (1) the greater the number of pairings of the stimulus with a primary reinforcer, (2) the more optimal the temporal contiguity, (3) the more salient the stimulus, and (4) the more predictive the stimulus is of the primary reinforcer. The amount of primary reinforcement and the drive level have little or no effect, consistent with the cognitive interpretation. Finally, intermittent pairing of the secondary and primary reinforcers produces slower extinction of secondary reinforcement value.
9. It does not appear to be possible to condition appetitive hunger and thirst drives to neutral environmental stimuli by pairing these stimuli simply with states of hunger or thirst where no food or water is present. However, it may well be possible to condition a stimulus to increase the hunger drive by pairing that stimulus with food consumption (the exact reverse of the procedure of pairing the stimulus with food deprivation).
10. Organisms learn to be *helpless*, not performing any responses to escape or avoid aversive events, as a result of earlier experience in which they had no control over the occurrence of aversive events in their environment. Such learned helplessness in the early environment of children might be a significant cause of depression.
11. Stress and ulcers are more likely to be produced by uncontrollable or unpredictable aversive events than by controllable or predictable aversive events.

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7 Animal Cognition

OBJECTIVES

1. To describe the capacity of animals to learn how to solve new problems of a particular type faster as they gain increased experience with problems of this type.
2. To discuss the capacities of animals to solve many problems at the same time and also to solve logically complex problems.
3. To describe the types of pattern (form), spatial (location), and temporal concepts that animals appear to possess either innately or through learning, including sameness versus difference, cognitive maps (spatial images) of their environments, some representation of time duration, ordering concepts such as single and double alternation, and the ability to count and discriminate numbers up to five or so.
4. To discuss the inferential capacities of animals to combine separate learning experiences so as to solve problems by insight.
5. To discuss learning by imitation of and through cooperation with other animals.
6. To discuss the language-learning capacity of chimpanzees.

The cognitive capacities of mammals are not strained by the elementary classical and instrumental conditioning tasks discussed in the previous two chapters. Mammals, especially primates, are capable of learning much more complex concepts and of using these concepts to solve problems and achieve goals. As previously discussed, they establish cognitive expectancies (sometimes called cognitive maps or spatial images) of the relations between places in their environment. Such maps have greater general usefulness in goal achievement than a series of *S-R* linkages. Besides complex spatial concepts, mammals also learn complex temporal concepts such as single alternation (for example, left, right, left, right . . .) and sameness and difference. They can learn to solve problems by imitating other animals and by using tools, and they can even learn to cooperate with each other to achieve a goal. Finally, chimpanzees, the most intelligent nonhuman primates, can acquire a surprising number of elementary components of symbolic processing found in human language. It is extraordinarily difficult to establish the conceptual capacities of any species, and no one now can make any definitive statements regarding capacity limits, but we can demonstrate some of the cognitive capacities of different species. This chapter surveys some of these.

LEARNING SETS

Object-Quality Set

One choice-learning device that psychologists have developed is the Wisconsin-General Test Apparatus. This apparatus, which has been used primarily with primates, generally consists of a horizontal tray with two or more food wells that can be covered by stimulus objects. Before each trial food is placed in the well under the correct object. An opaque screen prevents the monkey from seeing which well is baited with food. When the screen is raised, the monkey can displace one of the objects and pick up the food if the correct object is chosen. In a typical problem, the same two objects are used on each trial, and one of them is always correct. The organism can learn to choose the correct object regardless of its left-right position without great difficulty, although on the first problem it may require 30 or 40 trials to exceed a criterion of 90 percent correct.

In a classic study, Harry Harlow showed that after a series of such discrimination-learning problems, monkeys became far more proficient at learning each new problem—that is, they *learned how to learn*. After approximately 250 object-quality discrimination-learning problems, as soon as the monkey had chosen one of the two objects on the first trial of a problem, it knew that that object was either the correct or incorrect object and so chose it or the other consistently thereafter.[1] Such an organism has learned the general principle that a particular object will be consistently rewarded while the other is unrewarded in the choice situation and that these contingencies hold irrespective of position or other factors. In describing this situation, Harlow said the monkeys had developed a *learning set*.

Learning sets are abstract principles learned as a consequence of experience with a large number of related problems. The question is, How much does the development of a learning set depend on the degree of learning achieved within each problem? One might suppose it would take a rather large number of trials for each problem, particularly the early ones, for a learning set to develop over the course of a number of problems, but this is not so. As long as there are at least three or four trials per problem, development of a learning set depends more on the number of problems than on the number of trials per problem.[2]

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[1] H. F. Harlow, "The Formation of Learning Sets," *Psychological Review*, 1949 (56), 51-65.

Positional Set

Other types of learning sets have been developed in primates beyond the object-quality set just discussed. Harlow also developed a position-learning set—that is, a set to choose either the left or right position consistently, irrespective of the object that appears in that position. He also showed that a position-learning set could be acquired in conjunction with a previously acquired object-quality learning set. To demonstrate this Harlow took monkeys that had previously developed an object-quality learning set and presented them with positional discrimination-learning problems and object-quality discrimination-learning problems in alternating blocks. The speed of acquiring the object-quality discriminations was very rapid at the beginning and showed only a very small decline followed by recovery as animals developed position-learning sets for the positional problems. The speed of acquiring this positional discrimination began at a low level but ultimately approached the speed at which the object-quality discriminations were acquired. Harlow thus showed that an animal can learn and use more than one learning set depending on which is appropriate for the current problem.[3]

Other Learning Sets

Harlow and others have also demonstrated the capacity of monkeys to acquire reversal learning sets. Throughout a series of trials the choice of a particular object was consistently rewarded, but the reward was intermittently switched to the other alternative, so that choice of that object was required in order to receive reward. Over such successive *discrimination reversal* problems, monkeys became faster and faster in reversing their discrimination as soon as they received one error. The object-quality learning set and the discrimination reversal learning set can be acquired and maintained at the same time.[4]

Closely related to the reversal learning set is the *response-shift* learning set. In response-shift learning a monkey is rewarded on the first trial no matter which object he chooses, but to receive a reward on the second trial the monkey must choose the other object. On each succeeding trial the monkey must choose the object it did not choose on the preceding trial. Monkeys can acquire a set to solve this type of problem. In problems with three or more alternatives, monkeys can develop an *oddity* learning set—that is, if all the objects but one are identical or equivalent (share some set of properties), the monkey can develop a set to pick the dissimilar object. The animal can also develop a *sameness* learning set, a set to choose one of the identical objects rather than the odd object.

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[2] M. Levine, B. Levinson, and H. F. Harlow, "Trials per Problem as a Variable in the Acquisition of Discrimination Learning Set." *Journal of Comparative and Physiological Psychology*, 1959 (52), 396-98. R. C. Miles, "Discrimination Learning Sets," in A. M. Schrier, H. F. Harlow, and F. Stollnitz (eds.), *Behavior of Nonhuman Primates*, Vol. 1. New York: Academic Press, 1965.

[3] Harlow, "The Formation of Learning Sets."

[4] *Ibid.*

Theory: Error Factors

Harlow developed a theory of error factors that in one form or another has been the predominant approach to understanding the development of learning sets.[5] His theory is that the development of a learning set involves suppression of an organism's response biases. For example, an organism might come into a learning situation with a bias to choose a particular position, say the left position. (If the bias that the organism brings is not to choose a given position, it might be to base its decision on a position cue rather than an object-quality cue.) Either of these alternatives might be referred to as a position preference. In the case where position is the relevant factor, development of a position-learning set would strengthen a position-cue bias weaken an object-quality bias (or a bias to choose a particular position if that position is the wrong one). In an object-quality discrimination, of course, the animal must overcome any position preference and learn to base its choice on form or color cues.

Another error factor identified by Harlow is a tendency to shift responses from trial to trial. If a monkey made the left choice on one trial, he may tend to pick the right position on the next trial, regardless of the relevant cue. Such a *response-shift bias* might exist if the monkey is attempting to explore the environment. This bias may facilitate the development of a response-shift learning set, but it must be eliminated in the development of other types of learning sets.

Another factor identified by Harlow is *stimulus perseveration*, a tendency to pick the same object (or choose the same position) on each trial regardless of whether it has been rewarded. Elimination of such an error factor would facilitate all learning regardless of which cues are relevant.

Because monkeys seem capable of maintaining two response sets at virtually the same level that they maintain one, it seems unlikely that the development of a set can be explained entirely in terms of the elimination of maladaptive biases (error factors). Of course, a demonstration that monkeys can maintain four or five learning sets at once would more conclusively rule out this theory as the sole explanation of learning set development. It is difficult to state precisely what organisms have learned when they have acquired a learning set, but it seems reasonable to assume that they have not just suppressed error tendencies but have actually acquired some concepts or "hypotheses" about the regularities that underlie the learning situation.

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[5] H. F. Harlow, "Performance of Catarrhine Monkeys on a Series of Discrimination Reversal Problems," *Journal of Comparative and Physiological Psychology*, 1950 (43), 231-39. H. F. Harlow, "Learning Set and Error Factor Theory," in S. Koch (ed.), *Psychology: A Study of a Science*, Vol. 2. New York: McGraw-Hill, 1959.

Phylogenic Comparison and Genetic Differences

Learning sets have been investigated most extensively in primates, but they have also been demonstrated in other mammals, including rats, cats, raccoons, and dolphins. Demonstrations of learning set phenomena in species below mammals, however, have not been terribly impressive. The formation of learning sets has been demonstrated in birds, and to a lesser extent in amphibians and fish, but there have been many many failures in working with such species.[6] Species with more highly developed cerebral cortices tend to show more rapid development of learning sets, and ablations of the cerebral cortex diminish the capacity to form learning sets (more seriously than they diminish the capacity to master individual problems).

There has been very little work on learning sets in invertebrates, partly because of the difficulty of demonstrating learning sets in lower vertebrate species. The little work that has been done has yielded mostly negative results, though there is a successful demonstration by Mackintosh and Mackintosh of the development of a limited degree of reversal learning set in octopuses.[7] This was particularly surprising because fish apparently do not show progressive improvement in successive reversals (reversal learning set). This is another demonstration of the impossibility of arranging species in a simple linear order of increasing intelligence, because some species that are considered lower in an overall phylogenetic scale of intellectual development are superior to "higher" organisms in particular respects.

[6] K. L. Kirk and M. E. Bitterman, "Habit Reversal in the Turtle." *Quarterly Journal of Experimental Psychology*, 1963 (15), 52-57. J. M. Warren, K. H. Brookshire, G. G. Ball, and D. V. Reynolds, "Reversal Learning by White Leghorn Chicks." *Journal of Comparative and Physiological Psychology*, 1960 (53), 371-75. D. H. Bullock and M. E. Bitterman, "Habit Reversal in Pigeons." *Journal of Comparative and Physiological Psychology*, 1962 (55), 634-39. J. Wodinsky and M. E. Bitterman, "Discrimination Reversal in the Fish." *American Journal of Psychology*, 1957 (70), 569-76. M. E. Bitterman, J. Wodinsky, and D. K. Candland, "Some Comparative Psychology." *American Journal of Psychology*, 1958 (71), 94-110. J. M. Warren, "Reversal Learning by Paradise Fish (Macropodus opercularis)." *Journal of Comparative and Physiological Psychology*, 1960 (53), 376-78.

[7] N. J. Mackintosh and J. Mackintosh, "Performance of *Octopus* over a Series of Reversals of a Simultaneous Discrimination." *Animal Behavior*, 1964 (12), 321-24.

COMPLEX CHOICE LEARNING

Concurrent Discrimination Learning

One typical difference between human verbal learning experiments and most animal learning experiments involves the number of associations the subjects are required to learn. Typical paired associate learning designs use eight to 12 pairs of items. The use of mnemonic instruction techniques enables human subjects to master hundreds of word pairs in an hour or so. By contrast, conditioning and discrimination-learning experiments with animals typically require the learning of a single association (though the organism may develop more than one association in solving the problem). For example, in two-choice discrimination-learning experiments, organisms may not only learn what to choose but also what not to choose (two associations). Nevertheless there have not been many learning experiments that have studied the capacity of animals to master large numbers of independent associations simultaneously.

One exception is a concurrent-discrimination-learning experiment by Hayes, Thompson, and Hayes. Chimpanzees were given five, ten, or 20 object-quality discrimination problems to master simultaneously. A single trial consisted of the presentation of each of the five, ten, or 20 pairs of choices one after another. Naive chimps and chimps with extensive prior work with individual binary choice problems were studied, and both groups of chimps mastered as many as 20 simultaneous problems, although the experienced chimps attained high levels of correct performance more rapidly than the naive chimps. After three trials, the experienced chimps were responding correctly to 70 to 80 percent of the pairs, but naive chimps required about ten trials to reach the same level. Notice that while these chimps are simultaneously learning twenty problems, they are maintaining only one learning set, that of object-quality.[8] Since there is apparently very little forgetting between sessions in this type of discrimination learning, it seems likely that chimpanzees could learn far more than 20 simultaneous discrimination problems. Indeed, one imagines that for many mammals the number of associations learned and maintained at a high level during the course of a lifetime is so large as to defy experimental assessment.

Complex Conditional Learning

In concurrent-discrimination learning the chimp must process several attributes in the course of making up to 20 binary choices in each trial, and each one of these binary choices must be more difficult than a binary choice made in isolation. For instance, if an incorrect or irrelevant attribute-value of an object in one choice is similar to a correct attribute-value in another choice, there may be some interference in learning. However, concurrent-discrimination learning is similar to simple-discrimination learning in that the chimps have to attend to only one or two attributes in making each choice.

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[8] K. J. Hayes, R. Thompson, and C. Hayes, "Concurrent Discrimination Learning in Chimpanzees." *Journal of Comparative and Physiological Psychology*, 1953 (46), 105-7.

In contrast, Nissen presented chimps with 16 binary discrimination-learning problems in which the stimulus objects differed on five dimensions, with two values on each dimension: size (large, small), color (white, black), form (square, triangle), margin (absent, present), and peg (absent, present). To make a correct choice in each of the 16 problems, the chimp had to attend to all five stimulus dimensions. This experiment assesses the capacity to process several attributes simultaneously and is obviously a much harder task than simple concurrent-discrimination learning. It is not surprising that the task was enormously difficult for the chimps.

There were a total of 17,740 trials in 401 sessions of 25-100 trials each. Training was accomplished in stages. At first two attributes were relevant to each solution, then three dimensions, then four, and finally all five. Each time a new cue was added, the correct values of the previous cues remained the same. Notice that adding a new cue dimension doubles the number of possible combinations of relevant attribute values. In fact, adding a new cue interfered with previous learning—that is, the addition of a cue was generally accompanied by a decrease in accuracy in responding to the previous cues. Nevertheless, one chimp out of three mastered all 16 problems.[9] Mastery of such a complex set of discrimination problems undoubtedly requires mediation via the chunking mechanism.

PATTERN CONCEPTS

To a human being, a square and a diamond are distinct forms that can be easily discriminated. By contrast, Boycott and Young showed that octopuses have great difficulty in discriminating such shapes. Moreover, Sutherland has shown that in some instances octopuses do not discriminate a form from its mirror image (versus right/left) at all. Similar investigations with rats, dogs, monkeys, and children have demonstrated that mirror-image discriminations are difficult but obtainable. An interesting finding in this research is that up/down mirror-image reversals are discriminated more easily than right/left reversals.[10] A discrimination-learning paradigm allows us to investigate pattern-discrimination abilities in nonverbal animals and thus determine the innate and learned capacities of each species, to represent different patterns. Species with no ability to chunk presumably depend upon innate pattern analyzers for combinations of different features in order to master discrimination-learning problems, whereas higher organisms can chunk features to form a single new concept representative. Such organisms therefore should be able to discriminate any two distinct patterns of features.

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[9] H. W. Nissen, "Analysis of a Complex Conditional Reaction in Chimpanzee." *Journal of Comparative and Physiological Psychology*, 1951 (44), 9-16.

Of particular interest is the ability to determine whether two spatially separated patterns match or mismatch, and to respond accordingly. Higher mammals, particularly primates, possess or can learn this matching concept, as demonstrated by their abilities to acquire sameness learning sets and oddity learning sets. A typical variation of the matching task involves choosing one object from an array that matches a target object presented earlier or in a different spatial position. In a modified version of this procedure, a delay is interpolated between presentation of the target and presentation of the array, so as to study an organism's memory capacities.

SPATIAL CONCEPTS

We have concluded previously that in simple classical and instrumental conditioning an organism learns a complex cognitive structure that incorporates knowledge about a set of goal-achieving responses rather than a specific skeletal response. Perhaps the most definitive evidence in support of this position has been derived from experiments on maze running in rats.

In the 1940s there was a vigorous debate between cognitive psychologists such as Tolman and *S-R* psychologists such as Hull and Spence concerning what a rat learns when it masters a maze. According to the cognitive psychologists, the rat acquired a cognitive map of the layout of the maze and location of the food. Such cognitive maps are examples of the S_1R-S_2 expectancies discussed in Chapter 4 as *SR-K* expectancies. Since reinforcement (K) is considered by a cognitive psychologist to be the stimulus outcome (S_2) of making response R in situation S_1, we shall use the $S_1R\text{-}S_2$ terminology whenever the outcome (S_2) is not an obvious primary reinforcer such as food, water, or pain. Furthermore, it should be noted that the R in an $S_1R\text{-}S_2$ expectancy is not an actual motor response, but the idea node for one. For many purposes R may be like a relation between the two stimulus situations—for example S_2 (is to the right of) S_1.

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[10] B. B. Boycott and J. Z. Young, "Reactions to Shape in *Octopus vulgaris* Lamarck." *Proceedings of the Zoological Society of London*, 1956 (126), 491-547. J. Z. Young, "Learning and Discrimination in the Octopus." *Biological Reviews*, 1961 (36), 32-96. N. S. Sutherland, "Visual Discrimination of Orientation and Shape by the Octopus." *Nature*, 1957 (179), 11-13. N. S. Sutherland, "Visual Discrimination of Orientation by *Octopus*." *British Journal of Psychology*, 1957 (48), 55-71. N. S. Sutherland, "Visual Discrimination of the Orientation of Rectangles by *Octopus vulgaris* Lamarck." *Journal of Comparative and Physiological Psychology*, 1958 (51), 452-58. N. S. Sutherland, "Visual Discrimination of Orientation by *Octopus*: Mirror Images." *British Journal of Psychology*, 1960 (51), 9-18.

According to the early *S-R* psychologists, the rat learned specific stimulus-response associations when it mastered a maze that involved acquiring a chain of *S-R* pairs in which each response yielded the stimulus for the next response. The final response in the chain resulted in reinforcement, which strengthened the *S-R* associations leading up to reinforcement.

Attempts to discriminate experimentally between these theories produced results that were in accord with the cognitive approach. The *S-R* theories can only be modified to account for these findings by introducing substantial complexity. Several of the most important phenomena supporting the theory that rats acquire spatial cognitive maps are outlined in the following sections.

Place Versus Response

Suppose a rat learns to turn to the right in a simple T maze to obtain food how can we tell whether the rat is learning to make a right-turning response or whether it is developing a concept of where the food is located? One method for distinguishing between these alternatives involves moving the starting alley (the stem of the T) 180° to the other side of the crossbar. (See Figures 7-1 and 7-2.) If the food is placed in the same end of the crossbar, a left turn rather than a right turn is now required to reach it.

Two simple designs for the comparison of place versus response learning employ this method. In a transfer design, the approach alley is flipped 180° after the rat learns to turn right to obtain food in the original maze, and transfer of training is tested. If the rat makes the same right-turn response, it demonstrates that what is learned is that particular response, but if the rat turns left, it demonstrates that the rat learned to approach a particular place.

The second alternative is to flip the starting alley before each trial during learning. In one condition the end of the crossbar in which the food is placed is also switched on each trial, so that a righthand turn is always required. (See Figure 7-2.) In the other condition the food remains in one end of the crossbar so that the rat must learn to approach the same place, but the required turning response alternates between trials. (See Figure 7-1.) The dependent variable here is speed of learning.

Although more experiments to compare place versus response learning

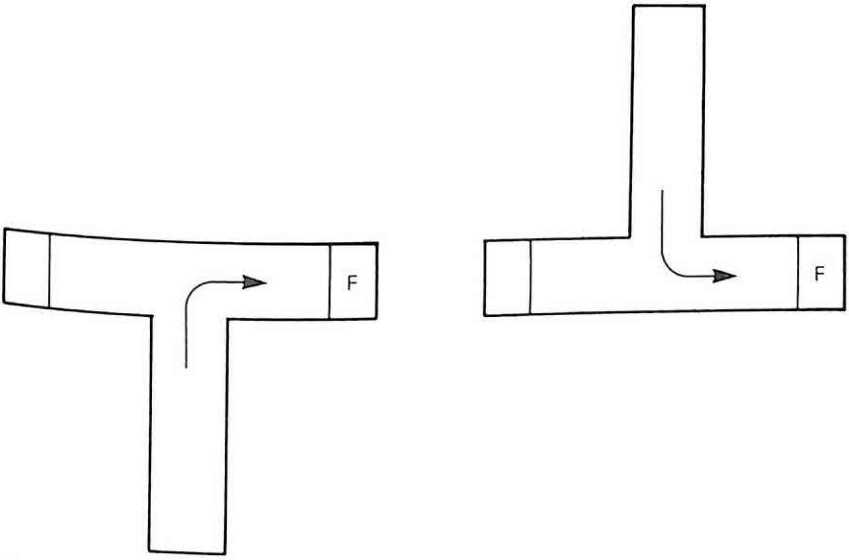

Figure 7-1. A place-learning experiment with the starting alley flipped 180° from trial to trial. Food is at a constant place in the room.

support the dominance of place over response, there are enough experiments supporting response over place to suggest that the animals can learn either. An excellent paper by Frank Restle summarizes the variables that effect the relative dominance of place versus response learning. Basically,

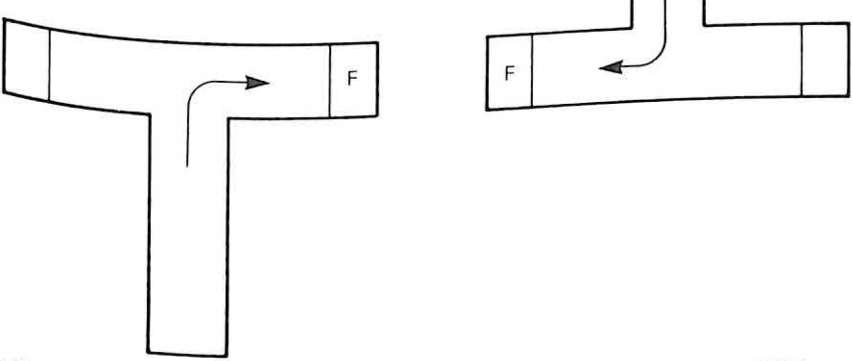

Figure 7-2. A response-learning experiment with the starting alley flipped 180° from trial to trial. Food follows a right turn in the maze.

when there are rich intramaze and extramaze cues, place learning is dominant, but when such cues are eliminated, only response learning is possible. (Even such so-called "response" learning could be considered a special kind of place learning, where place is defined relative to the stem of the T or to the rat's bodily position as it moves down the stem to the choice point.) In any event, when rats have the opportunity to respond on the basis of either place or response cues, place is dominant, confirming the expectations of the cognitive psychologist.[11] However, what is most important is not whether place or response is dominant in any particular species, but whether the species has the capacity to form cognitive maps for the spatial locations of things in the world. The place versus response experiments demonstrated that rats have this capacity.

Spatial Orientation and Detours

A further demonstration that rats learn cognitive maps that incorporate relationships between stimuli in the environment was provided in an experiment by Tolman, Ritchie, and Kalish. In this experiment rats first ran the maze (Figure 7-3) to obtain the reward in the goal box. Following this

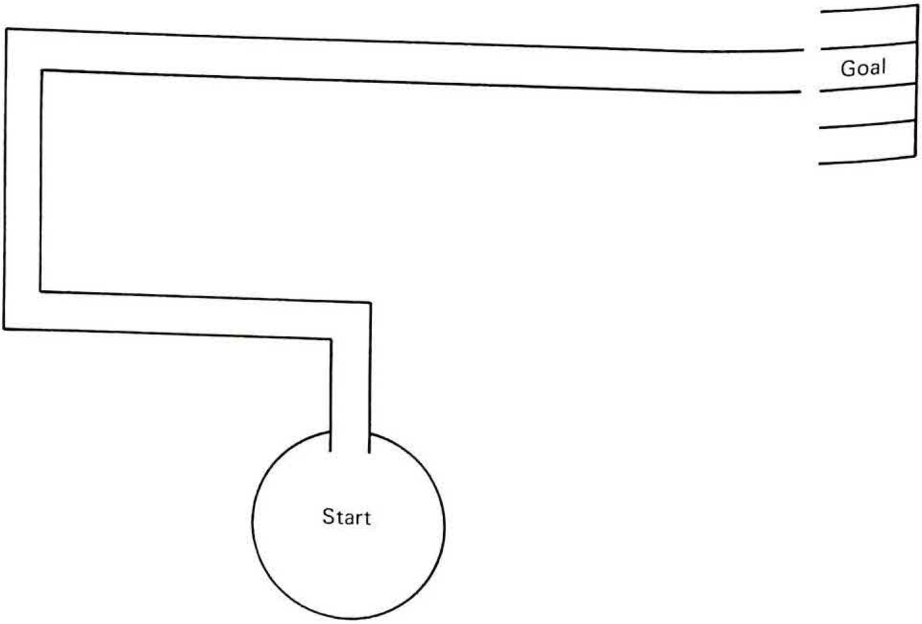

Figure 7-3. The Tolman, Ritchie, and Kalish initial learning layout.

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[11] F. Restle, "Discrimination of Cues in Mazes: A Resolution of the 'Place-vs.-Response' Question." *Psychological Review*, 1957 (64), 217-28.

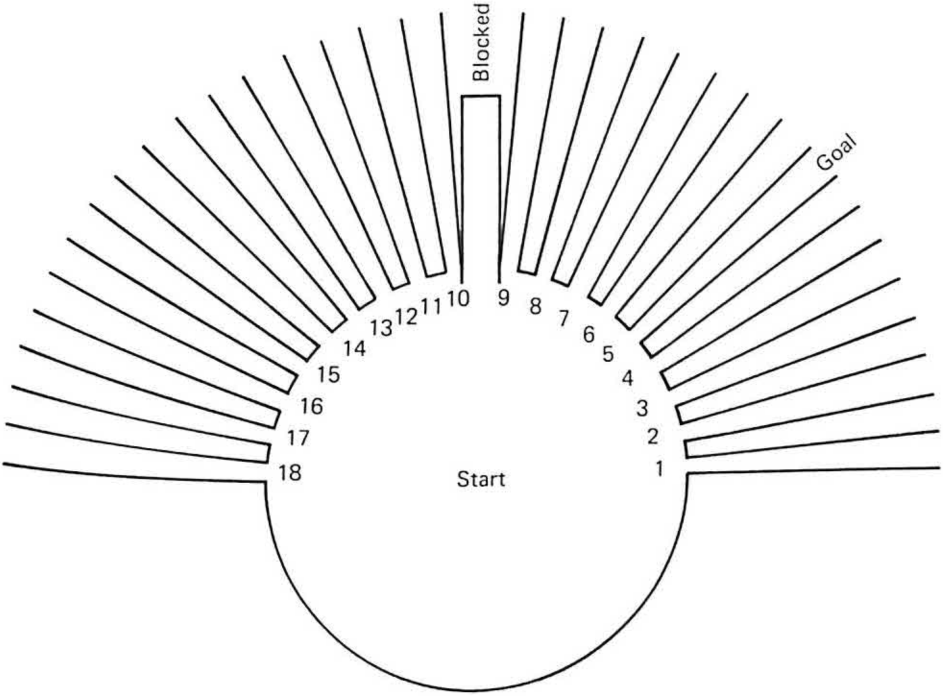

Figure 7-4. The Tolman, Ritchie, and Kalish transfer test layout.

training, the original path to the goal box was blocked and the rats were provided with a variety of paths radiating from the starting table (Figure 7-4). The rats tended to select a path that pointed in the general direction of the goal box (path 3, 4, 5, 6, or 7) rather than one that started near the original path (a path such as 8, 9, 10, or 11). Such an experiment succeeds only when there are distinctive extramaze cues to mark the location of the goal box within the room.[12]

This experiment was concerned with the ability of rats to use spatial concepts to choose a direct path to the goal when a previously learned indirect path was blocked. In contrast, the so-called *detour* experiment requires that the animals select an indirect path to the goal when the most direct path is blocked. Some species have great difficulty learning to do this, especially if the obstacle is transparent so that the goal can be seen but not accessed through the blocked path. These species will bump their heads into the wall many times before they learn to make the appropriate detour, while other species will detour almost immediately or after a short trial period. More intelligent species generally learn detour problems faster than less intelligent species, but not always.

[12] E. C. Tolman, B. F. Ritchie, and D. Kalish, "Studies in Spatial Learning: I. Orientation and the Short-Cut." *Journal of Experimental Psychology*, 1946 (36), 13-24.

Latent Learning and Exploration

Latent learning experiments provide further support for the theory that animals such as the rat can learn spatial cognitive maps. Of the several experimental designs that have been classified as latent learning designs, we shall consider only two here.

In the latent learning design employed by Blodgett and by Tolman and Honzig, one group of animals (the latent learning group) is run in a maze for a number of trials without reward, while a second group is run with reward. The introduction of reward to the first group promptly reduces the number of errors made in running the maze. In fact after reward is introduced, the latent learning group almost immediately catches up to the continuously rewarded group. The rats seem to be learning the path leading out of the maze even in the absence of an extrinsic reward.[13] This design has some defects. For instance, the rats were removed from the maze when they got to the end, and this itself may have been rewarding: the rats may have learned a sequence of responses that led to escape from the maze. This explanation seems particularly plausible in that there was a reduction in the number of "errors" made (blind alleys entered) before the reward was introduced.

A second paradigm, introduced by Lashley, involved an initial period of free exploration of a complex maze. Following exploration, a reward was introduced at some place in the maze. Learning to reach the reward was facilitated by the previous period of free exploration compared to a control group without such prior exploration.[14] If we assume that the rats did not selectively perform and learn turning responses leading to the place where the reward was later placed prior to introduction of the reward, the evidence suggests that the basis for the positive transfer from the exploratory activity was the learning of a cognitive map of the maze.

Drive Discrimination

A rat can be trained to turn one direction in a T maze to obtain water when it is thirsty and to turn in the other direction to obtain food when it is hungry. Drive—that is, hunger or thirst—provides a discriminative cue that indicates the correct turning response. Consider a situation in which a group of rats is exposed to the T maze when they are neither hungry nor

[13] H. C. Blodgett, "The Effect of the Introduction of Reward upon the Maze Performance of Rats." *University of California Publishings in Psychology*, 1929 (4), 113-34. E. C. Tolman and C. H. Honzik, "Introduction and Removal of Reward, and Maze Performance in Rats." *University of California Publishings in Psychology*, 1930 (4), 257-75.

[14] K. S. Lashley, "A Simple Maze: With Data on the Relation of the Distribution of Practice to Rate of Learning." *Psychobiology*, 1918 (1), 353-67. G. W. Haney, "The Effect of Familiarity on Maze Performance of Albino Rats." *University of California Publishings in Psychology*, 1931 (4), 319-33.

thirsty. Over the course of a number of trials each rat is forced to turn in each direction an equal number of times to become acquainted with the location of the food and water. In subsequent trials when they are actually hungry or thirsty, these rats make fewer turning errors than a control group that was not previously exposed to the maze.[15] Since in the original exposure the same set of cues was associated equally often with each response, there should be no bias to turn in one direction. Even if such a bias exists, however, it cannot explain the positive transfer to both hunger and thirst conditions. Because such positive transfer is obtained, we must conclude that the rats are learning cognitive maps—*SR-K* associations—rather than *S-R* associations.

A related design involves latent learning in which the animal is not completely satiated but rather experiences a strong but unrelated drive. For instance, animals that are hungry and are learning to turn right in a T maze to obtain food can be exposed to water in the left arm of the maze incidentally. Some experiments find positive transfer to subsequent trials wherein the animal is thirsty, but many others do not.[16] Apparently strong drive conditions impair learning that is unrelated to that drive, perhaps because of a failure to pay attention to the necessary cues.

Learning Without Responding

Clever experiments by Gleitman and by MacNamara, Long, and Wike have demonstrated that rats can learn what leads to what in a T maze even though they make no running or turning responses themselves. Such responses were unnecessary—indeed, not possible—because the rats were carried through the maze in little baskets or cable cars. Subsequent transfer or extinction trials showed that the rats learned the location of the goal. Hungry rats passively carried through the maze to both related (food) and unrelated (water) goals demonstrated as much learning on subsequent free learning trials as hungry animals that were exposed to both goals but were responding freely and actively from the beginning.[17] Here is a further

[15] C. L. Hull, "Differential Habituation to Internal Stimuli in the Albino Rat." *Journal of Comparative Psychology*, 1933 (16), 255-73. R. Leeper, "The Role of Motivation in Learning: A Study of the Phenomenon of Differential Motivational Control of the Utilization of Habits." *Journal of Genetic Psychology*, 1935 (46), 3-40. H. H. Kendler, "The Influence of Simultaneous Hunger and Thirst Drives upon the Learning of Two Opposed Spatial Responses of the White Rat." *Journal of Experimental Psychology*, 1946 (36), 212-20. K. W. Spence, G. Bergman, and R. Lippitt, "A Study of Simple Learning under Irrelevant Motivational Reward Conditions." *Journal of Experimental Psychology*, 1950 (40), 539-51.

[16] See Kimble, *Conditioning and Learning*, pp. 228-32.

[17] H. Gleitman, "Place Learning Without Prior Performance." *Journal of Comparative and Physiological Psychology*, 1955 (48), 77-79. H. J. McNamara, J. B. Long, and E. L. Wike, "Learning Without Response under Two Conditions of External Cues." *Journal of Comparative and Physiological Psychology*, 1959 (49), 477-80.

demonstration that the motor response itself can be irrelevant to what is learned when an organism masters a maze.

Extinction Without Responding (Latent Extinction)

Finally, a maze running response to obtain a reward in a goal box can be partially extinguished by passive exposure to the goal box when it does not contain food.[18] This is to say, the maze-running behavior can be extinguished by the absence of reinforcement even if the animal does not make any active responses. This is entirely reasonable if what the animal has learned in the first place is a cognitive map one component of which is an association between a particular location and the presence of some reward. Subsequent exposure to that place without the reward weakens this association and produces a decrement in performance.

TEMPORAL CONCEPTS

Inhibition of Delay

Inhibition of delay in classical conditioning, a phenomenon we discussed earlier, illustrates one kind of temporal concept present in some organisms. The phrase refers to a progressive increase across trials in the delay between *CS* onset and the *CR* in delayed or trace conditioning. After a number of conditioning trials organisms appear to delay the *CR* so that it occurs just before the *US*. Increasing the *CS-US* interval results in a longer delay between *CS* onset and the *CR* (as well as a slowing down of the rate of learning).

As was mentioned in Chapter 4, a similar capacity to learn time intervals has been demonstrated in the free response paradigm. Recall that with a fixed-interval schedule an organism is reinforced for its first response after a fixed time from the previous reinforcement, and that birds and mammals demonstrate acquisition of a concept of the time interval by showing an increase in the rate of responding near the end of the interval.

Alternation

It has been repeatedly demonstrated that fixed alternation of reinforcement and nonreinforcement for performance of some response in *go no-go* tasks produces corresponding alternation in the speed or magnitude of the response. Birds and mammals learn to perform the conditioned response more rapidly on trials where they expect reward than on alternate trials in which there is no reward. We have some idea of the lower phylogenetic limits of the capacity to form temporal alternation concepts, because Mackintosh demonstrated that goldfish do not show such response alternation with alternating reward schedules. Similarly, birds and mammals demonstrate faster extinction following regular alternation than following irregular 50 percent conditioning schedules, but fish show no difference in extinction in the two cases.[19]

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[18] J. P. Seward and N. Levy, "Sign Learning as a Factor in Extinction." *Journal of Experimental Psychology*, 1949 (39), 660-68. J. Deese, "Extinction of a Discrimination Without Performance of the Choice Response." *Journal of Comparative and Physiological Psychology*, 1951 (44), 362-66. H. Moltz, "Latent Extinction and the Reduction of Secondary Reward Value." *Journal of Experimental Psychology*, 1955 (49), 395-400.

Birds and mammals also demonstrate an ability to master single alternation in *choice* tasks—tasks in which they must choose first the left alternative on one trial and then the right alternative on the next trial, continuing on a left-right (single alternation) schedule to receive rewards.[20] The phylogenetic dividing line between species that are able and those that are not able to master single-alternation tasks also falls somewhere between fish and birds.

Double Alternation

A single-alternation schedule is of the form LR LR LR, etc., a double alternation of the form LLRR LLRR LLRR, etc. Double alternation is considerably more difficult to master than single alternation. Hunter demonstrated that only a very small number of rats were capable of mastering a double-alternation maze-running task.[21] A substantial amount of time is required to run one trial in a maze, and considerable time elapses between the performance of a right or left turn on one trial and the performance of a left or right turn on a subsequent trial, so it may be the rat's capacity to remember a sequence of turns rather than its capacity to develop an alternation concept that limits performance. Schlosberg and Katz devised a lever-pushing task: the rat was required to push the left lever twice, then the right lever twice, and so on, with less time between responses than in the Hunter demonstration. Rats were able to master this task.[22]

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[19] D. W. Tyler, E. C. Wortz, and M. E. Bitterman, "The Effect of Random and Alternating Partial Reinforcement in Resistance to Extinction in the Rat." *American Journal of Psychology*, 1953 (66), 57-65. N. J. Mackintosh, "Reward and Aftereffects of Reward in the Learning of Goldfish." *Journal of Comparative and Physiological Psychology*, 1971 (76), 225-32. R. C. Gonzalez, R. M. Eskin, and M. E. Bitterman, "Alternating and Random Partial Reinforcement in the Fish with Some Observations on Asymptotic Resistance to Extinction." *American Journal of Psychology*, 1961 (74), 561-68.

[20] W. S. Hunter, "The Temporal Maze and Kinaesthetic Sensory Processes in the White Rat." *Psychobiology*, 1920 (2), 1-17.

[21] *Ibid.*

[22] H. Schlosberg and A. Katz, "Double Alternation Lever-Pressing in the White Rat." *American Journal of Psychology*, 1943 (56), 274-82.

Counting and Number Sense

Correct performance in double alternation appears to require a capacity to count to two. The question that arises is, What is the counting capacity of different species? The most extensive and best-controlled work on this question was by Koehler and his coworkers on the numerical capabilitites of birds. In one experiment birds learned to peck one of two choice cards that had the same number of black spots as a previously presented sample card. By varying the pattern configuration, size, and shape of the spots, the possibility that the birds were responding on the basis of these other characteristics was excluded.

Birds can learn to discriminate numbers when stimuli are presented either simultaneously or successively. Koehler and his associates showed that birds could be trained to eat a specific number of grains (one, two, three, four, or five) out of a much larger number that were simultaneously offered when some type of punishment was delivered for eating more than that number. Birds could also learn to eat a specific number of grains out of a larger number when the grains were presented successively rather than simultaneously, even when the interval between grains varied between one and 60 seconds.

In another experiments birds were presented with a long row of closed boxes. Some boxes were empty, some contained one or more baits. The birds were successfully trained to raise the lids on the boxes one at a time until a specific number of baits had been obtained. Notice that since the number of baits inside the boxes varied, the number of baits to be obtained was independent of the number of boxes that had to be opened. Furthermore, birds could learn up to four counting problems simultaneously. Specifically they could learn to secure two baits if the lids were black, three baits if the lids were green, four if the lids were red, and five if they were white.

Besides performing an excellent series of experiments on counting in birds, Koehler has also given us an amazing anecdote: One day a jackdaw was given the task of opening boxes to secure five baits. The baits were distributed across the first five boxes in the following order: one bait in the first box, two in the second, one in the third, none in the fourth, and one in the fifth. On one trial the jackdaw went home to its cage after opening the first three boxes and eating only four baits. As the experimenter was recording that one too few baits had been eaten, the jackdaw came back to the line of boxes and initiated the following astounding behavior: It bowed its head once before the first box, twice before the second (where it had eaten two baits), once before the third, and then went on to open the fourth, which contained no bait, and finally the fifth, when it secured its last bit of food. The jackdaw then left the line of boxes and immediately returned to its home cage. The jackdaw not only completed the task after an interruption, it also appeared to demonstrate that it remembered the exact distribution of baits in the boxes it had opened on that trial.[23]

Thompson, Mayers, Robertson, and Patterson have found single neurons in the cat's association cortex that encode number concepts. Out of 500 neurons studied, they found five that responded selectively to the second, fifth, sixth (two neurons), or seventh stimulus in a series. The auditory or visual character of the stimuli was not important, nor was the rate of presenting the stimuli over a range of from one to five seconds between stimuli.[24]

INFERENCE

In an abstract logical system, the term *inference* refers to the combining of two or more expressions (generally propositions) to derive a new expression (proposition). Perhaps the most important example of such inference is provided by the chain rule—if A implies B and B implies C, then A implies C. In human semantic memory, thinking (which we shall discuss in Chapter 10) involves both the retrieval of previously stored information (propositions) and the inferential combination of such propositions to produce new propositions. Human associative memory is constructed in such a way that the number of propositions that we can derive from our memory via an inferred combination of propositions is much greater than the number of directly stored propositions. A variety of studies in animal problem solving, insight, tool-using, and the like have investigated this inferring capacity in lower organisms. The present section will discuss some of the more important investigations of this kind.

Trial-and-Error Problem Solving

Between Darwin's *The Origin of Species* (1859) and Thorndike's classic *Animal Intelligence* (1911), there was an interval that might charitably be referred to as the romantic period in the study of animal intelligence, when all sorts of exotic mental powers were attributed to lower organisms, largely on the basis of personal anecdotes and uncontrolled observations. C. Lloyd Morgan's famous parsimony canon, which states that an action that can be explained in terms of a lower mental faculty, should not be interpreted in terms of a higher mental faculty, and Thorndike's carefully controlled experimental studies put an end to the romantic period.

When Thorndike studied the behavior of cats and dogs in escaping from problem or puzzle boxes (in which a latch could be opened by pulling a string or lever), he observed no sudden insight on the part of the animals in solving these problems, but rather a gradual improvement in performance stemming from trial-and-error behavior that accidentally resulted in performance of the latch-opening response. Once the animal had performed that response, the latency of performing the act decreased with progressive strengthening of the association between the response and the escape. Although the responses were sometimes rather exotic, elementary instrumental conditioning theory was sufficient to explain the behavior. No new theoretical concepts were required, and Thorndike effectively said so.[25]

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[23] O. Koehler, "The Ability of Birds to 'Count'." *Bulletin of Animal Behavior,* 1950 (9), 41-45.

[24] R. F. Thompson, K. S. Mayers, R. T. Robertson, and C. T. Patterson, "Number Coding in Association Cortex of the Cat." *Science,* 1970 (168), 271-73.

Insight

Köhler rightly objected that Thorndike's failure to demonstrate insightful learning could not be considered evidence that this capacity does not exist in animals other than human beings. A cat cannot possibly show insightful learning in one of Thorndike's puzzle boxes because the mechanism linking the response and release from the box is far too difficult for the organism to understand. Köhler studied the ability of chimpanzees to solve problems that lent themselves more to insightful solution. In one problem chimpanzees learned to use a long stick to rake in a piece of food lying outside the bars of the cage. In other problems chimps had to pile boxes up to reach food suspended from the ceiling, or attach two short sticks together to form one long stick in order to reach food. According to Köhler, his wild adult chimpanzees showed sudden insightful solutions to these problems, not gradual trial-and-error behavior.[26]

In explaining such problem-solving behavior, Köhler (and others in the Gestalt and ethological traditions) have placed great emphasis on the perception of relationships between stimuli as an essential component of insightful problem solving. As we have previously discussed, animals are capable of forming rather complex spatial concepts that surely involve just such relationships between different objects. But most of the evidence is on the side of those who say that the formation of spatial concepts and the solution of insight problems require some period of learning various components of the required problem-solving behavior. For example, although there were some differences in their results, both Birch and Schiller demonstrated that some degree of prior experience in using sticks is very important in solving Köhler's stick problems. The backgrounds of Köhler's chimps are unknown, since they were wild, but presumably they included experience in the use of sticks. Furthermore, Schiller demonstrated that in the more complex stick problem, in which two sticks must be acquired from outside the cage and then joined together to reach food, performance was definitely facilitated by stepping the chimps through a graded sequence of problems that involved an increasing number of subtasks of the overall task. Finally, Köhler observed that chimps have an innate tendency to manipulate sticks—licking, chewing, splitting, banging, poking, hammering, and thrusting them. Performing these acts later provides the ape with the necessary experience to use the stick in the problem-solving situation, though some degree of generalization is exhibited whenever the stick is used in a somewhat different setting from that in which it was originally manipulated.

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[25] E. L. Thorndike, "Animal Intelligence: An Experimental Study of the Associative Processes in Animals." *Psychological Review Monograph Supplement,* 1898 (2), 1-109.

[26] W. Köhler, *Mentality of Apes*. London: Methuen, 1927.

Chimps can also undoubtedly solve problems by inferential combination of separately learned "facts," habits, or associations. Köhler's stick-using insight problems were less than ideal for investigation of the inferring process, since prior experience was uncontrolled. Schiller's design —teaching several component habits in isolation, then having them be combined to solve a more complex problem—was better controlled.[27]

Tool Using

For a while it was popular to describe humans as the tool-using or tool-making animal. As a result studies of tool using or tool making among lower organisms assumed some importance. Of course Köhler's studies that demonstrate the use of sticks by chimps to solve problems are examples of tool using, and the joining together of two short sticks to make one long stick is an example of tool making. Tool using is apparently rare in organisms lower than man, but a number of fascinating examples have been collected. While living with a group of chimps in Tanganyika, Goodall observed them poking sticks into ant nests or termite holes to draw out ants or termites to eat. The chimps select their sticks or grasses very carefully for this purpose, rejecting ones that are too short in favor of more adequate tools. Chimps are also reported to use sticks to poke bees' nests to obtain honey, and to open palm nuts by hammering them with rocks.[28]

An analogous use of sticks to obtain food has been observed in the woodpecker-finch. This bird picks up a cactus spine or twig and pokes it into a crack in a tree to drive out an insect. As the insect leaves the crack, the finch drops the tool and seizes the insect. These finches have been reported to reject twigs that are too short or too pliable and to carry the

[27] H. G. Birch, "The Relation of Previous Experience to Insightful Problem Solving." *Journal of Comparative Psychology*, 1945 (38), 367-83. P. H. Schiller, "Innate Constituents of Complex Responses in Primates." *Psychological Review*, 1952 (59), 177-91.

[28] K. R. L. Hall, "Tool-Using Performances as Indicators of Behavioral Adaptability." *Current Anthropology*, 1963 (4), 479-94. K. R. L. Hall, "Animals That Use Tools." *Animals*, 1965 (7), 16-21.

same tool in their beaks as they investigate a succession of trees. The most fantastic anecdote concerning such birds is the report that on one occasion a finch attempted to use a forked stick that would not enter the crack. After a couple of futile attempts, the bird "saw what was wrong," turned the stick around, broke off the fork, and resumed working. Unfortunately, charming though the report is, single occurrences count for very little in science.

Another animal that uses a tool is the sea otter. When it is feeding on mussels, it dives to the bottom of the sea to obtain a large stone, comes to the surface, places the stone on its chest, and breaks a mussel shell by banging it repeatedly against the stone. Even insects sometimes use tools, as in the case of the solitary digger wasp that holds a small pebble in its mandibles, using it as a hammer to pound dirt into its nest.

What can we conclude about the cognitive capacities of animals that use tools in various ways? Unfortunately not very much. The instances of tool use in insects and possibly birds may be almost completely innate, no different in kind from innately determined courtship, nest building, or song behavior. In some cases, imprinting or some other form of prepared learning might be involved. It is possible that young sea otters and chimps learn tool-using behavior by imitating their parents. Even when tool-using behavior such as the stick manipulation of chimps is not innately specified, it probably depends very heavily on innately specified tendencies. In most instances it would appear that no inference process need be assumed.

Inferential Problem Solving

The most satisfactory studies of inference or reasoning consisted of a series of experiments performed by Maier on how rats combine separate experiences or habits. One of Maier's simplest demonstrations of reasoning involved the combination of two experiences. First, a rat had a period of free exploration of an elevated Y maze each of whose three arms terminated on a distinctive goal (or start) table. Second, the rat was fed on one of the tables. Then the hungry rat was placed on one of the other tables and permitted to run the Y maze. Normal rats were able to combine these two separate experiences and make correct choices at the choice point of the Y maze on the first trial about 90 percent of the time (chance being 50 percent). A critical degree of brain damage to the cerebral cortex reduced this *reasoning* score to a value close to chance; however even brain-damaged rats could still *learn* the correct turn in the Y maze, without the use of reasoning, though their learning was somewhat impaired. Maier argued from this that reasoning ability and learning ability in rats were at least partially separate factors.[29] It seems logically necessary that any associative memory possess at least this chaining capacity for the inferential combination of separately learned associations. Nevertheless, greater experimental support for the hypothesis in a variety of species would be desirable.

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[29] N. R. F. Maier, "Reasoning in White Rats." *Comparative Psychology Monographs*, 1929 (6), No. 29. N. R. F. Maier, "The Effect of Cerebral Destruction on Reasoning and Learning in Rats." *Journal of Comparative Neurology*, 1932 (54), 45-75. N. R. F. Maier. "A Further Analysis of Reasoning in Rats: II. Comparative." *Psychological Monographs*, 1938 (15), No. 1, Serial No. 73.

IMITATION

Herbert and Harsh allowed cats to observe another cat obtaining a food reward by a simple manipulation such as pulling a string or pressing a lever several times. The observing cats subsequently solved the same problems more quickly than control cats that had not had the opportunity to learn by imitation. Vicki, a young chimpanzee adopted by the Hayeses and raised in their home, would imitate an enormous variety of actions performed by her human parents: pounding a stake with a hammer, applying makeup to her face, sharpening pencils, using a screw driver to pry off the lid of an empty paint can, etc. Vicki could imitate immediately or at some delay after observing the activity. Young animals of many species are said to learn what to eat and what not to eat by imitating their parents. Young chicks learn to scratch and peck more readily if given the opportunity to observe another bird performing these responses. Other examples of imitation include the previously discussed process of song acquisition in some species of birds, where exposure to adult song induces a similar song dialect in a young bird. The mockingbird copies the songs of many different species, and we all know about parrots. Finally, consider the tendency of fish to follow the leader, or of sheep and birds to eat in the same place or to run off in alarm because one member of the group has initiated such action. These examples are not all the same kind of imitation process, however, and some distinctions must be made.[30]

Learning Versus Performance (Imprinting Versus Contagion)

Once again it is important to distinguish between learning and performance. When one bird squawks in alarm and flies off and the others quickly follow, we may be observing behavior that falls rightfully into the category of imitation, but it is imitation of performance, not an example of learning by imitation. The birds already know how to fly off, and the association between the actions of the first bird and the flying response is either innate or previously learned. The action of the first bird is a *releasing stimulus* which triggers a response that happens to be nearly identical to that of the stimulus. This same sort of thing presumably applies to schooling in fish or to their tendency to eat when they observe another fish eating a certain food at a certain place. Such contagious imitation is undoubtedly of substantial survival value, but it is not an example of learning by imitation and will not be discussed further in this section. It is important to determine which changes in performance result from actual learning and which are contagious imitation.

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[30] M. J. Herbert and C. M. Harsh, "Observational Learning by Cats." *Journal of Comparative Psychology*, 1944 (37), 81-85. K. J. Hayes and C. Hayes, "Imitation in a Home-Raised Chimpanzee," *Journal of Comparative and Physiological Psychology*, 1952 (45), 450-59. W. H. Thorpe, *Learning and Instinct in Animals*. Cambridge, Mass.: Harvard University Press, 1963.

Social-Emotional Facilitation

If the observing animal performs better in learning some new task than a control animal with no opportunity to observe another animal perform that task, it is possible that the reasons are social or emotional or both. That is, the animal may either be calmed down or aroused, either of which might be beneficial to learning the task. A control group that is exposed to an animal in the situation but that does not perform the relevant action assesses the amount of social-emotional facilitation.

Perceptual Learning (Copying)

Another potentially confounding factor in the study of learning by imitation is perceptual learning, where performance is improved by simply observing the stimulus situation or the stimulus consequences of action in that situation but there is no learning of the actions themselves. To test for the possibility of purely perceptual learning of the attributes of the stimulus situation, a control group can be exposed to the stimulus situation without having a demonstrator present. It does not seem likely that this would bias the effects of most studies of imitation, but it is a logical possibility.

More likely instances of perceptual learning underlying alleged imitation occur in the way humans learn speech, and the way birds learn songs (copying). In neither case does it appear that the observing individuals pay much attention to the *actions* of producing speech or song, or that the opportunity to observe beak and throat movements has any special effects on later "imitation" of the product. Rather what appears to be more important is to hear speech or song so as to acquire the appropriate featural, segmental, and/or phrasal units via the perceptual learning process. Once the organism has acquired the perceptual chunks for speech or song, those subsequent productions that result in sounds that activate the same perceptual analyzers will tend to be selectively repeated. This leads to selective development of speech or song that matches the sounds previously heard in the environment. Copying is distinguished from true imitation by virtue of the irrelevance of observing the *action* of the demonstrator organism.

Prepared (Instinctive) Imitation

Humans and probably other primates such as chimpanzees exhibit truly general imitation, which is the ability to learn any action within an organism's behavioral capacity by observation of another individual performing that action. Lower species appear to be genetically prepared to learn some behavior by imitation but unable to learn other behavior by that method.[31] Here as in other forms of learning the concept of preparedness proves useful for purposes of phylogenetic comparisons. For example, the abilities of young birds and mammals to learn by imitation which foods to eat and not to eat are very likely specially prepared instances of learning by imitation. The same probably holds true of many aversions. It has been observed that young primates show little fear of snakes or other stimuli that adults react to with extreme fear. It is presumed that under normal conditions young primates acquire these fears by observing adults of the same species exhibiting the fear reactions to these stimuli. Although chimpanzees and many other primate species undoubtedly possess more general capacities to imitate than lower mammals and birds, the learning of such aversions by imitation is probably especially prepared in all species, including human beings.

The most highly prepared form of imitation would be a single-contingency form of imitation in which observation of the action itself, independent of the consequences of the action, resulted in learning of the action by the observer. Such single-contingency learning must invariably be highly prepared; otherwise it would be dysfunctional.

General Imitation

It seems likely that only primates are capable of truly general imitation, though this is by no means definitely established.[32] Furthermore, even in primates, few experiments have controlled for all the possible confounding factors that underlie facilitation of performance by observation. However, several principles of imitation have been suggested and are worth considering.

First, across the range of imitation studies a wide variety of the types of learning appear to be produced by imitation. Such types include conceptual expectancy learning (cognitive map learning), attentional learning (what to pay attention to or where in the environment to orient oneself), sensory motor-skill learning (where the components themselves are in the behavioral repertory but the sequence is new), and finally, social-emotional learning (including fears, dominance, and social conformity).

Second, imitation is more successful when the demonstrator is from the same species as the observing organism. (Chimps like Vicki have frequently learned by imitating human beings, so this is not a rigid rule.) Variations in the tendency to imitate different models within the same species probably at all solicited help from every partner they were paired with and generalized the solicitation gestures from one problem to another.[36]

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[31] Thorpe, *Learning and Instinct in Animals*.
[32] *Ibid.*

SYMBOLIC PROCESSES

Something very exciting is happening in the study of animal cognition. We are discovering that chimpanzees can master some rudiments of human language to an extent undreamed of ten years ago. As superior training methods are devised, our estimates of the cognitive capacity of chimps will probably require progressive upward revision. We are in no position now to state the linguistic and more general cognitive characteristics of chimpanzee intelligence. The capacities demonstrated so far may or may not be close to the limit. In any event the results obtained so far are amazing.

Expressive Medium

There have been some heroic but ultimately unsuccessful efforts to teach chimpanzees to talk. The Hayeses raised Vicki as a member of their family and exposed it to considerable verbal and intellectual stimulation, but in six years Vicki learned only four sounds that had any resemblance to English words. It is now clear that the problem in teaching verbal language to a chimp was with the medium and not with the message: Chimps can understand spoken language, but they cannot learn to speak.

Gardner and Gardner, however, demonstrated that their chimp Washoe could understand and produce elements of a gestural language, American sign language for the deaf. Almost simultaneously Premack demonstrated the capabilities of a chimp, Sarah, to manipulate a language in which words were represented by plastic chips of various colors and shapes. In another set of experiments, chimps have been taught to operate computer terminals and to judge the grammaticality of strings of symbols produced on display screens.[37] Apparently chimps have considerable ability to learn a syntactic system and to judge whether strings are grammatical or ungrammatical within that system.

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[36] M. P. Crawford, "Further Study of Cooperative Behavior in Chimpanzee." *Psychological Bulletin*, 1936 (33), 809.

[37] R. A. Gardner and B. T. Gardner, "Teaching Sign Language to a Chimpanzee." *Science*, 1969 (165), 664-72. D. Premack, "A Functional Analysis of Language." *Journal of Experimental Analysis of Behavior*, 1970 (14), 107-25. D. Premack, "Language in Chimpanzee?" *Science*, 1971 (172), 808-22. A. J. Premack and D. Premack, "Teaching Language to an Ape." *Scientific American*, October 1972, pp. 92-99. D. M. Rumbaugh, T. V. Gill, and E. C. vonGlasersfeld, "Reading and Sentence Completion by a Chimpanzee (Pan)." *Science*, 1973 (182), 731-33. D. M. Rumbaugh, E. C. VonGlasersfeld, H. Warner, P. Pisani, and T. V. Gill, "Lana (Chimpanzee) Learning Language: A Progress Report." *Brain and Language*, 1974 (1), 205-12.

depend on such factors as familiarity, the dominance-submission relationship, and sex or affiliation, but such factors have yet to be adequately investigated. Some of these may not be of great interest for the study of learning itself. For instance there is a tendency for an imitation method to be less effective when the model and observer are of the opposite sex.[33] It may just be that interest in the model as an individual interferes with attending to the model's behavior.

Third, it has been noted that the opportunity to observe an individual actually learning a task produces more efficient subsequent learning on the part of the observer than does observation of an animal performing the task. Similarly, Darby and Riopelle reported that superior imitation learning results from seeing the demonstrator make a mistake than from seeing it choose the correct alternative in a two-alternative object-quality discrimination task.[34]

Higher primates such as chimpanzees can definitely develop a learning set to imitate—that is, the tendency to imitate can be learned. The Hayeses specifically tried to induce Vicki to imitate. When she was a young infant she was consistently reinforced for very elementary imitations, and this undoubtedly contributed substantially to her avid imitating tendencies in later life.[35] Darby and Riopelle experimentally demonstrated a systematic increase in ability to profit from imitation in an object-quality discrimination learning task. When an observer animal watched only the first choice of the demonstrator in each of a series of problems it improved progressively in its ability to make the correct response on its first choice after observation. Thus, a learning set for imitation can be developed in much the same way as other learning sets.

COOPERATION

Pairs of young chimpanzees can be trained to solve problems through cooperation. Crawford gave pairs of chimpanzees a problem in which a heavy box containing food could be retrieved by pulling two ropes. He reports that cooperative behavior did not occur spontaneously, but that it could be trained in three stages. First, the animals learned to pull together by responding to an external cue. Then each learned to watch the other and to join in pulling at the proper time. Third some chimpanzees developed gestures—hand and arm movements and sometimes vocalizations—to solicit pulling by their partner. Chimps that did any soliciting

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[33] *Ibid.*

[34] C. L. Darby and A. J. Riopelle, "Observational Learning in the Rhesus Monkey." *Journal of Comparative and Physiological Psychology,* 1959 (52), 94-98.

[35] Hayes and Hayes, "Imitation in a Home-Raised Chimpanzee."

These successful attempts differed from their unsuccessful predecessors not only in their choice of medium but also in their selection of a nonphonemic language. In a phonemic language like English, words are composed of phonemes, articulatory subunits that correspond roughly to the individual letters, that have no meaning in themselves. The gestures employed by the Gardners and the chips employed by Premack cannot be broken down into analogous physical subunits. It is not clear whether chimpanzees can learn phonemic languages, but it undoubtedly facilitates the learning of small vocabularies to use a word-based rather than a phoneme-based language. Washoe, the Gardners' chimp, has the largest vocabulary of any chimp, about 160 words. This is a fairly small vocabulary, and it is probably simplest in such cases to learn a unitary symbol that corresponds to each word. Only when vocabulary reaches into the thousands or tens of thousands does it become more practical to learn a relatively small set of phonemes (perhaps thirty to fifty) that words can be constructed from.

Training Procedures

To get Washoe to use sign language, the Gardners employed a combination of methods involving molding, prompting, and imitation. Molding refers to a process of teaching a sign by first molding the hands into the desired shape. Prompting, which is similar to molding, involves helping the chimp with difficult signs in the early stages of learning. Imitation the Gardners encouraged at first by explicitly rewarding Washoe for imitating a variety of things they did. This produced a high tendency on Washoe's part to imitate human beings, which easily transferred to imitating signs.

Premack employed a shaping procedure typical of instrumental conditioning. He began his instruction of Sarah by placing the plastic name of a piece of fruit alongside the fruit and requiring Sarah to place the name on the language board in order to obtain the fruit. This was easily accomplished. Next Sarah was forced to discriminate between the names of different fruits in order to receive a given piece of fruit. In the next stage Sarah was required to select the symbol corresponding to the donor of the fruit—that is, to the person then in the room running the experiment. At this point Sarah was producing two-word phrases such as "Mary apple" or "Randy banana." After this Sarah learned basic concepts and acquired an ability to handle progressively longer sentences.

Learnable Concepts

We shall now discuss the concepts for which chimps can learn names. The most difficult aspect of learning the name of a concept is learning the concept itself; if the concept itself is learnable, attaching a name to it is a relatively straightforward process. What really limits the basic vocabulary of a chimp is not so much the process of assigning some symbol to a concept as it is the process of learning new concepts of various degrees of abstraction. As a consequence largely of the work of Premack and the Gardners, we now know that chimpanzees can master an astounding variety of concepts.

Names. Naturally chimps can learn noun concepts—their own names, the names of other chimps, the names of various people, the names of objects. Chimps can also learn the names of verbs, ("give," "wash," "cut," "insert," "tickle"); the names of locations; even the names of states of emotion ("sorry," "funny").

Negation. Chimps can learn the concepts of negation as applied to verbs ("not insert," "not wash") and relational nouns ("not same as"). I have not been able to find much discussion of negation as applied to nouns, as in "not a grape" or "not an apple," but presumably a chimpanzee that had mastered negation as well as these noun concepts would also understand the meaning of negation as applied to those concepts.

Same-different. As might be predicted from their ability to perform matching and oddity tasks, chimps can master the concepts of same and different in linguistic tasks.

Questions. Chimps can also learn the meaning of *wh*-questions. *Wh*-questions are cued by giving a special question symbol—"?"—as a part of a sentence—for instance, "*X*?*X*," which the chimp answers by replacing the question symbol with the symbol for same, or "*X*?*Y*," which the chimp answers by replacing ? with the symbol for different. Sarah can also answer yes-no questions of the form "Is *X* the same as *X*?" by choosing the symbol for "yes" and "Is *X* the same as *Y*?" by choosing the "no" symbol. Sarah has somewhat more difficulty in answering yes-no questions that involve the difference relation, such as "Is *X* different from *X*?" or "Is *X* different from *Y*?" It remains to be seen whether a chimp can attain a high level of performance on all four sets of yes-no questions.

Object classes. Chimpanzees can learn object classes such as fruits and bread stuffs (bread and cookies).

Properties. Members of an object class of the above type do not have any single obvious quality in common, but members of other classes, termed property classes, do have such attributes in common and chimps can learn these classes as well. For example they can learn color concepts such as green or brown and shape concepts such as circle, triangle, or square. The chimps can successfully generalize property concepts to new objects from examples observed during training.

Dimensions. Not only can chimps learn the names of specific attributes (values along some dimension, for instance green or square), they can also learn the names of the dimensions themselves, such as color and shape. Such competence can be demonstrated by giving a chimp such as Sarah a question of the form "Green is?" and noting that she will choose the word for color. She is presented with a negative question such as "Red is not?," she will choose the symbol standing for shape. A yes-no question to test the same competency might be the sentence "Is brown the color of chocolate?," to which the chimp should answer "yes," or "Is brown the color of a grape?," to which the chimp should answer "no." Once again it would be interesting to test the competence of chimps in answering yes-no questions involving negation, such as "Is not brown the color of apple?," to which the chimp should answer "yes," or "Is red not the color of apple?," to which the chimp should answer "no." However to my knowledge chimpanzee ability to answer such yes-no questions involving negations of attributes and dimensions has not been tested. Investigations of chimp language competence have understandably focused on demonstrating competence rather than its lack. As our understanding of chimpanzee language competence increases, there will be greater interest in assessing specific shortcomings in language ability. Moreover, with increased experience there will be greater confidence that such demonstrations of incompetence transcend the specific linguistic medium and training procedures employed by the investigator.

Copula and conjunction. Sarah has learned the copula concept ("is") but apparently prefers to delete it. She also understands the concept of conjunction ("and") although that concept is typically not explicitly represented as a symbol in communication to and from her. There may be something very basic about these easily deletable concepts.

Singular versus plural. Sarah has also learned to distinguish between singular and plural forms of verbs and of the copula (is versus are = is + plural). Sarah demonstrated such competence by replacing the ? in sentences such as "Red and yellow is ? shape" by the symbol for plural, indicating she knows that a compound subject requires the plural form of the copula verb.

Quantifiers. Sarah has some degree of mastery of quantifiers ("all," "one," "none," "several"), which she demonstrates by correctly performing the action when given commands such as "Sarah insert one cracker (in) dish," "Sarah insert some cracker (in) dish," "Sarah insert one candy (in) dish," "Sarah insert all candy (in) dish," etc. She demonstrates understanding of these quantifiers by answering *wh*-questions of the form "? crackers is square?" where none, one, several, or all of the crackers before her might be square. Once again, Sarah successfully generalized the quantifier concept from original training in which she was asked questions regarding shapes to new test questions regarding color of objects.

Prepositions. Sarah has learned prepositions such as "in," "on," "under," "to the side of," and the like. Like the same-different construction, these prepositions have two arguments; unlike same-different constructions, however, prepositional relationships are asymmetrical—that is, the *X* and *Y* in "*X* different from *Y*" can be interchanged without changing the meaning, whereas interchanging *X* and *Y* in "*X* under *Y*" does change the meaning. Sarah attends to the order of the arguments in sentences involving prepositions, and given a command like "Put red on green," she will correctly place a red card on a greed card. Thus, not only does Sarah understand prepositional terms, she can also use order as a syntactic cue in understanding sentences.

Names and concepts. Sarah also understands the concept "name of," and she knows that certain symbols are the names of certain objects. When asked to give a description of an object such as a grape, Sarah will respond with green rather than with brown, and with round rather than with square. She will give the same analysis of the symbol that stands for the concept grape. However if Sarah is asked to give a property description of the "name of a grape," she will respond according to the color and shape properties of the plastic symbol used as the name of the object. Such ability to distinguish between the symbol and its referent demonstrates a degree of abstract competence that was heretofore unsuspected in animals below human beings.

Implication. Perhaps the most difficult concept that Sarah has mastered is the sentential relation "implies." Consider the sentences, "If Mary take red then Sarah take green" or "Sarah take apple implies Mary give Sarah chocolate." Premack reports that Sarah took longer to learn this conditional relation between propositions than to learn most other concepts. She did learn it, however, and once she learned it she successfully generalized the concept to new contexts.

Phrases and Propositions

The Gardners report that once Washoe had learned a few single words, she began spontaneously to produce multiword utterances (typically two or three words) without further training. Thus, Washoe produced such phrases as "give me tickle," "open food drink" (meaning "open the refrigerator"), "go in," "go out," "go sweet" (to be carried to a raspberry bush), "open flower" (to be let through a gate to a flower garden), "listen dog" (at the sound of an unseen dog barking), "listen eat" (at the sound of an alarm clock signalling meal time), and "water bird" (the name of a duck). Apparently chimps, like human beings, naturally combine words into phrases standing for previously unnamed objects and into propositions involving nouns in conjunction with relational terms. Premack explicitly taught such combinations to Sarah, and we have already seen the surprisingly long sentences that she could understand. Many of the individual concepts that Sarah mastered—dimensional names, the copula ("is," "are"), singular and plural quantifiers, "name of," "implies," prepositions, and verbs—have complete meaning only as a part of a larger phrase or proposition. With respect to syntactic competence, we have already discussed how Sarah used order as an important syntactic cue to distinguish the asymmetrical arguments of verbs and prepositional terms.

In addition, Sarah may have a certain degree of hierarchical phrase structure capability. As an example of what this means, consider the following sentence to which Sarah responds appropriately: "Sarah, insert apple pail banana dish." This sentence means that Sarah is to insert the apple into the pail and the banana into the dish. The hierarchical phrase structure can be indicated by parentheses, which show that the words go together to form phrases as follows: {Sarah [insert (apple pail) (banana dish)]}. As the bracketing indicates, *apple* and *pail* go together to form a phrase, and *banana* and *dish* to together to form another phrase. At a higher level, *insert* applies to both *apple pail* and to *banana dish*, and at the highest level, it is *Sarah* who is to carry out both of these insertion actions. This embedding of words into lower-order phrases, of lower-order phrases into higher-order phrases, and of higher-order phrases into an entire proposition or sentence is what is meant by hierarchical phrase structure.

Sarah appears to understand such sentences, at least in the sense of being able to perform the instructions communicated by the sentence, so it is reasonable to conclude that she has some capacity for handling hierarchical phrase structure. If Sarah lacked the capacity to deal with such hierarchical phrase structure, it might be predicted that she would only carry out the first action—inserting the apple into the pail—and not carry out the second action at all, since the subject and verb were not repeated in immediate contiguity with the second phrase ("banana dish"). Another error an organism without hierarchical phrase structure capacity might make would be to follow strict contiguity and insert the banana into the pail as often as the apple is inserted into the pail. Finally, an organism lacking hierarchical phrase structure capacity might refuse to respond to the sentence at all, if it was too complex to understand. Since Sarah is able to respond to such sentences correctly, it suggests some phrase structuring capacity.

Of course we do not know *how* Sarah manages to understand such sentences, and it would be premature and very likely wrong to conclude that Sarah's hierarchical phrase structure capacity was qualitatively similar to that of human beings. Moreover, from Sarah's capacity to handle hierarchical phrase structure for compound objects, we cannot conclude that she could handle other hierarchical phrase structures, for example the sentence "Sarah, insert the banana (which is) on the dish into the pail."

The linguistic competence of chimpanzees is a fascinating area. If the ridicule of an uninformed politician does not stop this line of research, we may soon have profound insight concerning the nature of human thinking as illustrated by the basic ways in which human thinking is similar to and different from that of our nearest living relative.

SUMMARY

1. Higher vertebrates acquire learning sets that speed the solution of problems that are similar to previously solved problems. Many lower vertebrates and most invertebrates appear to lack this learning-to-learn capacity.
2. Chimps can master at least 20 two-choice object discrimination problems, with trials on all problems mixed together.
3. Chimps can learn a complex conditional discrimination requiring attention to five simultaneous stimulus dimensions.
4. Higher mammals possess the concepts of the sameness versus difference for two objects.
5. Rats (and presumably other mammals) can learn cognitive maps with S_1R-S_2 expectancies for spatial relationships between locations. The R term in such an expectancy is not a peripheral motor response, but an abstract idea node for a response, much like the relation between the two stimulus situations S_1 and S_2.
6. Higher organisms demonstrate some kinds of time duration concepts by their ability to learn delays between events, and time responses accordingly.
7. Higher animals learn temporal order concepts such as single alternation (LRLR . . .) and even double alternation (LLRR . . .).
8. Some birds can count to five or thereabouts (temporal number concept) and can discriminate between stimuli on the basis of the number of spots present, in the face of variations in the pattern, size, and shape of the spots (spatial number concept).
9. The inferential capacities of animals other than man are not known. Tool using and tool making in chimps may be one example of inference, but the best existing example may be the inferential combination of two maze experiences by rats: exploration of a maze followed by reinforcement in one location of the maze.

10. Imitation has many different meanings:
    (1) contagious imitation, where the response of one organism provides an innate releasing stimulus for the same response in another organism; (2) perceptual learning (copying), where the sensory product, such as speech or song, of the demonstrator's actions is learned by the observer as a model for its own responses, but the actions that produced the product need not be observed; and finally both (3) prepared imitation and (4) general imitation, where the opportunity for observation of the demonstrator's actions is critical. The tendency to imitate can be increased in frequency, at least in higher primates.
11. Chimps have been taught to cooperate in solving a problem.
12. Chimps can understand simple spoken and sign language and can produce a word-based sign language, but they lack the vocal capacity to speak to any satisfactory degree.
13. Chimps can learn many concepts including: object (noun) concepts, action (verb) concepts, locations, emotions, negation, same-different, yes-no and *wh*-questions, object categories (fruits, bread stuffs), properties (green, brown, circle, triangle), dimensions (color, shape), copula ("is"), conjunction (and), singular versus plural, quantifiers (all, one, none, several), prepositions (in, on, under), the distinction between a concept and its name, and implication (if . . . then . . .).
14. Chimps spontaneously combine words into novel phrases, and with training they can understand some moderately complex phrase structures.

8 Verbal Short-Term Memory

OBJECTIVES

1. To discuss visual-sensory (iconic) memory, including persistence of vision and afterimages, focusing on the locus and nonassociative character of such memory storage.
2. To present the evidence for preattentional auditory-sensory (echoic) memory and to discuss whether it is a nonassociative activity trace analogous to iconic memory or mediated by the same kind of trace that underlies phonetic short-term memory for attended material.
3. To discuss somewhat longer-lasting graphic (visual) memory for verbal material.
4. To discuss the phonetic short-term memory, which plays a large role in our ability to dial a telephone number just spoken to us.

There is a subtle but important distinction in the area of learning and memory between coding and dynamics. *Coding* refers to all the *qualitative* properties of memory traces, including questions regarding the representation of events and concepts in the nervous system (what is learned), modalities of memory (verbal, spatial, and the like), and levels of encoding in a modality (such as phonetic versus semantic levels in verbal memory). By contrast, memory *dynamics* concerns the *quantitative* properties of acquisition, storage, and retrieval, and especially their variation with time. Dynamics concerns rates of learning, forgetting, and retrieval and how these rates depend upon various conditions.

To a substantial extent we can discuss the coding properties of learning, memory, and cognition independently of their dynamic properties and vice versa. This is not to say that there is no interaction between coding and dynamics. Clearly, there are interactions between the qualitative and quantitative properties of any process. However, distinctions between qualitative and quantitative aspects have proved useful in other sciences, and it appears to be possible to discuss coding and dynamics independently.

The scientific study of any complex subject such as learning and cognition would be impossible if we were not able to divide the whole into parts that are at least semi-independent of one another. Furthermore, it would be impossible to communicate information about such a complex subject matter without analyzing it into parts and teaching one part at a time. Chapters 8-11 are primarily concerned with coding in human learning and memory, while Chapters 12-15 are concerned with memory dynamics.

When someone says, "I have a good memory for faces but not for names," the implicit assumption is that there is some psychologically significant reason for distinguishing these two types of memory such that a person might be good at one and bad at the other. Psychologists classify memory traces in a variety of ways. The distinctions that have proved of the greatest psychological importance are those between different *modalities* (such as verbal versus visual-spatial memory) and those between different *levels* of a modality (such as phonetic versus semantic levels of the verbal modality).

Levels of encoding in verbal memory are discussed in Chapters 8, 9, and 10, and Chapter 11 discusses nonverbal memory for sensory-motor skills and images. Chapter 8 treats the lowest (most peripheral) levels of memory for verbal material: (1) *iconic very short-term memory* for visual sensory features, (2) *echoic very short-term memory* for auditory sensory features, (3) *graphic short-term memory* for letters or words and similar verbal units, and (4) *phonetic short-term memory* for the sound segments of words such as phonemes or syllables. Chapter 9 discusses coding in long-term verbal learning and memory. Chapter 10 treats coding of more complex propositional material in long-term semantic memory.

ICONIC MEMORY

Afterimages

Stare at some form fixedly (without moving your body, head, or eyes) for 30 seconds or so, then look away at a blank wall. If you maintain a fairly constant fixation, and if the illumination and reflectance conditions for your blank wall are appropriate, you should see an afterimage having the same form as the thing you stared at. Everyone experiences afterimages on many occasions, though we rarely pay attention to them. Although visual persistence and afterimages have long been studied by perceptual psychologists, an important study by George Sperling in 1960 was very influential in producing systematic consideration of these phenomena as examples of sensory memory.[1]

There are both positive and negative afterimages. If you stare at a light square on a dark background, the positive afterimage would be a light square on a dark background, whereas the negative afterimage would be a dark square on a light background. There is a persistence of the initial visual sensation (positive afterimage) for a brief period following the termination of a stimulus, which thereafter can change to a negative (reversed contrast) afterimage. Sometimes there is more than one cycle of positive and negative afterimages.

Persistence of Vision

The initial persistence of vision is often sharply distinguished from subsequent negative or positive afterimages. The physiological mechanisms of the initial persistence of vision are presumed to be a persistence of activation of the neurons originally activated by the stimulus at some level of the nervous system. Subsequent negative afterimages are presumed to be the result of fatigue of the elements previously activated. It is not known whether subsequent positive afterimages have a different physiological mechanism than the original persistence of vision. It seems parsimonious to assume that both persistence of vision and positive afterimages are produced by a continuation of activation of neurons activated by the original stimulus, while negative afterimages are produced by a depression in the activation of these neurons.

Many memory psychologists who study visual sensory memory and persistence of vision do not refer to these as afterimages. We shall use Ulric Neisser's term—*iconic memory*—to refer to these, but keep in mind that it is an unsettled question whether iconic memory differs from what perceptual psychologists mean by the term positive afterimage. Furthermore, studies of iconic memory have typically concentrated on memory for form information independent of whether the phenomenal contrast of the forms is dark on light or light on dark. Thus, most experimental studies of iconic memory have not rigorously excluded the possibility of contributions from negative afterimages. Under the conditions of many experiments, iconic memory may consist of an unknown mixture of persistence of vision and negative afterimages.

The study of iconic memory after Sperling differs in one potentially important respect from previous perceptual studies of afterimages: In studies of iconic memory the original visual stimulus is presented for a very short period, whereas in studies of afterimages it is fixated for many seconds or tens of seconds. A long fixation produces a strong negative afterimage, whereas the brief fixation characteristic of iconic memory experiments is presumed to produce primarily persistence of the original positive image with little or no negative afterimage. If this is true, then studies of iconic memory are concerned strictly with persistence of vision with little contribution from the fatigue or adaptational mechanisms that produce negative afterimages.

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[1] G. Sperling, "The Information Available in Brief Visual Presentations." *Psychological Monographs*, 1960 (74), Whole No. 498, 1-29.

The Capacity of Iconic Memory

The information storage capacity of iconic memory for the brief period following termination of the visual stimulus is substantial. For example, Averbach and Sperling presented an array of 18 letters as illustrated in Figure 8-1 for 50 milliseconds at a very high level of intensity and contrast with the background. Either immediately upon termination of the stimulus array or at delays of 0.1, 0.2, 0.3, 0.5, 1, 2, or 5 seconds following the array, they cued the subjects to report which letter occurred in one of the 18 possible positions. (Subjects were cued using combinations of tones, so as not to disrupt the icon, but it is also possible under some conditions to use visual cues, such as little arrows pointing to the position to be recalled.)

K	D	Z		B	J	L
N	S	P		W	G	X
T	M	R		C	V	D

Figure 8-1. A letter array of the type used by Averbach and Sperling.

If the probability of correctly recalling the cued letter is multiplied by the number of letters in the array (18), one obtains an estimate of the number of letters available in iconic memory at various delays following presentation of the array. The results of the experiment are illustrated in Figure 8-2 for two conditions: where the fields preceding and following the stimulus array were light and where they were dark. Figure 8-2 also demonstrates the number of letters that are available when subjects attempt to recall as many letters as possible from the array using the method of *whole report* rather than the *partial report* procedure developed by Sperling.

The results are striking. Immediately following presentation, from 14 to 17 of the 18 letters appear to be available in iconic storage. However, the partial report procedure demonstrates that visual iconic memory decays precipitously, especially with light pre- and post-exposure fields, which presumably create more interference with the icon than do dark pre- and post-exposure fields. Using light pre- and post-fields, within half a second

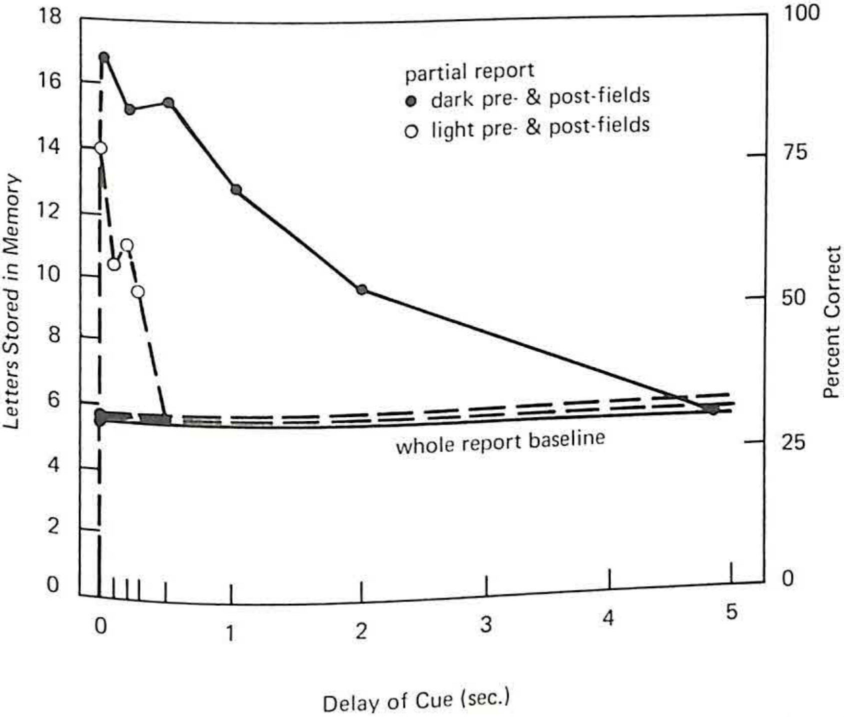

Figure 8-2. Decay of iconic memory to the whole-report baseline under conditions of light versus dark pre and post fields (from Averbach and Sperling by permission).

the iconic memory has decayed to an asymptotic level of approximately 4.5 items, which is precisely the number of items that can be reported using the whole report procedure characteristic of earlier visual memory span (span of apprehension) studies. Visual memory span, as assessed by the whole report procedure, is not very much affected by a delay in instruction to report. The reason for this is presumed to be that a subject begins scanning iconic memory immediately and that this scanning transfers the memory to some longer-lasting form. If by means of the partial report procedure attention is directed to a particular item in the array shortly after exposure, it can be scanned (read out of iconic memory) with a high degree of accuracy. However there appears to be a limit of around four or five items that can be scanned from iconic memory and retained in the longer-lasting memory, and this limit appears to be the same regardless of the rate of decay of iconic memory, since the same limit was approached under the conditions of either light or dark pre- and post-fields.[2]

Iconic memory is defined as the rapidly decaying memory component in excess of the visual memory span (amounting to approximately 10 or 12 items in the Averbach and Sperling experiment). The duration of this iconic memory can be anywhere from a few milliseconds (for arrays with low intensity and low contrast from the ground, short exposure duration, and light pre- and post-fields) to several seconds (for characters presented at high intensity and high contrast, long durations, and dark pre- and post-fields).

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[2] E. Averbach and G. Sperling, "Short-Term Storage of Information in Vision," in C. Cherry (ed.), *Information Theory, Papers from Symposium on Information Theory*. London: Butterworth, 1961, pp. 196-211.

Once the iconic component of memory for the visual array has decayed and subjects can report only four or five items, there is generally little further loss of memory. The nature of this slowly decaying component is the subject of some dispute. Some consider it verbal short-term memory; others consider it a more persistent form of visual memory. In any event, subjects appear to establish this more slowly decaying component by some sort of scanning of the visual array prior to complete degradation of the icon. The scanning is far too rapid to be verbal rehearsal, but whether the scanning process activates internal representatives in a visual or verbal modality is not clear.[3] Of course whatever the initial character of the memory established by visual scanning, the subject can rehearse the list within a matter of a second or so after termination of the stimulus, and thus establish a verbal memory trace.

The Locus of Iconic Memory

What is the locus of iconic memory? A number of findings indicate that long-lasting afterimages are localized in the retina, and it would be parsimonious to assume a retinal locus for iconic storage as well, since a known physiological mechanism exists that could produce such iconic memory. The mechanism is as follows: Light bleaches the pigment molecules in the visual receptors (rods and cones) of the eye, and this activates the peripheral neurons of the visual system. This activation in the retina is known to persist for some time following termination of the stimulus, possibly because the rods and cones require time to become unbleached.[4] On the basis of physiological knowledge concerning pigment bleaching and generator potentials in rods and cones, one would expect that most if not all of iconic memory is located in the rods and cones themselves.

Sakitt made an interesting verification of this expectation, by studying the vision of a person whose eyes had rods but no cones. Rods are primarily used in night vision, while cones are primarily used in daylight. Since rods reach maximum activation level at a much lower level of illumination than cones, this individual experiences considerable difficulty seeing in ordinary daylight, much as you have difficulty seeing in glare. When stimuli are presented in ordinary daylight, they are not seen by this subject; but if the subject closes her eyes after presentation of the stimulus, she can then see an icon of the presented stimulus! In fact she uses this technique in normal seeing, by going around blinking.[5]

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[3] G. Sperling, "A Model for Visual Memory Tasks." *Human Factors*, 1963 (5), 19-31.

[4] *Ibid*, p. 22. B. Julesz, *Foundations of Cyclopean Perception*. Chicago: University of Chicago Press, 1971, p. 34.

Actually there is no mystery why this takes place. At moderate daylight levels of background illumination, rods are at a maximum level for activation of visual neurons. At this level there is still plenty of unbleached pigment that will be differentially bleached by presentation of a stimulus. Since the chemical process that converts bleached pigment back into unbleached pigment takes time, after the eyes are closed the rods that have received the extra bleaching will maintain their potential to activate visual neurons somewhat better than the other rods, which allows the icon to literally emerge from the background. What the results definitively demonstrate is that the iconic storage—at least in this case—is entirely retinal, since the visual stimulus was not registered by the higher levels of the nervous system at the time it was presented.

Iconic Memory Is Nonassociative

A retinal locus for iconic storage strongly suggests that the memory is nonassociative. If an A is presented to two different locations, presumably two different but equivalent pattern representatives would be activated at both locations. Furthermore, there are presumably no associations from the character representative in one position to character representatives in adjacent positions. Somehow we know which locations are adjacent to each other, but the character representatives within the locations have no associations one to another.

The hypothesis that iconic memory is nonassociative has been tested directly. Under conditions fostering iconic memory, subjects were presented with two rows of alternating letters and digits (Figure 8-3). Recall of a character was cued in two ways. Both conditions involved presenting a cue character in one location with the subject instructed to recall the character to its immediate right. In one condition the cue was the correct character for the location it was in. (For example, in Figure 8-3 the cue might be "3 in the second position from the left in the first row for the array.") In the other condition a dummy character (either the letter A or the number 8) was presented, which subjects knew had not been in any location. For example, in Figure 8-3 8 might be presented as the number in the second position of the first row for the array. If all the cue character does is signal the location to be reported from iconic memory, and if there are no associations between character representatives in adjacent positions,

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[5] B. Sakitt, "Locus of Short-Term Visual Storage." *Science*, 1975 (190), 1318-19.

M 3 F 9 G 6

R 7 S 1 K 2

Figure 8-3. An alternating letter and digit array for testing the associative versus nonassociative nature of iconic memory.

then there is no reason a correct cue character should produce better recall than a dummy character, and this is exactly what was found.[6] No associations were formed between the adjacent characters in iconic memory. The memory is nonassociative, the pattern for an item being impressed upon a memory location.

The foregoing experiment studied visual memory at delays ranging from 200 milliseconds, where most of the memory was iconic, to 2 seconds, where iconic memory was essentially gone. The same equivalence of the two cuing conditions was obtained at all delays. This suggests that, at least under these conditions, even the more stable component of visual memory does not involve associations between character representatives, which is somewhat more compatible with the assumption that the persisting memory component is visual rather than verbal. However, it would be premature, and probably erroneous, to generalize from this result to the hypothesis that many levels of longer-lasting visual image memory are nonassociative. Some levels of image memory may be nonassociative, but the highest levels are likely to be associative.

Are Negative Afterimages Nonassociative Memory?

The negative afterimage that one sees under many circumstances results from differential adaptation or fatigue of the elements encoding the stimulus at some level of the visual modality. In their adapted or fatigued state, they are less susceptible to visual input, and therefore the complementary sensation of a figure of opposite contrast (or complimentary color) is obtained. Such differential perceptual adaptation is also very likely a nonassociative memory, in the same way that persistence of activation of elements is nonassociative. However, the nonassociative character of memory for negative afterimages has not been demonstrated.

Activational and Adaptational Memory

Throughout the nervous system elements may remain active for a period following the cessation of input from associated elements. This persistence

[6] W. A. Wickelgren and P. T. Whitman, "Visual Very-Short-Term Memory Is Nonassociative." *Journal of Experimental Psychology*, 1970 (84), 277-81.

of activation is a kind of nonassociative memory, even though it exists within an associative connection system. If an element is somewhat refractory (fatigued or adapted)—that is, it does not respond so easily or actively to input for a short time after it is activated—this is also a kind of nonassociative memory system.

ECHOIC MEMORY

Like many people, I typically pay little attention to people's names unless I think I will have to know the name later. Other characteristics of people are simply more important and more interesting than the arbitrary names people have. So it happens fairly often that when I am introduced to someone I realize a split second *after* hearing the name that I should have been paying more attention to the name at the time it was spoken. If I realize this soon enough I can sometimes "hear" the name in my mind almost as if it were being spoken again. This may be a persistence of audition (echoic memory) analogous to persistence of vision (iconic memory).

(We shall use Ulric Neisser's term, *echoic memory*, to refer to persistence of audition, and we shall consider echoic memory equivalent to what Robert Crowder and John Morton call *precategorical acoustic storage*.[7] The basic hypothesis is that there is an auditory or perhaps a phonetic analogue of visual iconic memory, such that the nodes activated by an auditory stimulus remain activated for some time after the stimulus is over.)

Four basic types of experiments have been employed to demonstrate the existence of echoic memory and to measure its duration: probe, modality, interference, and repetition studies.

Probe

Probe studies are analogous to the probe experiments used by Sperling to investigate iconic memory. Moray, Bates, and Barnett presented as many as four letters in sequence at each of four different locations in auditory space. (We can't discriminate different locations in auditory space nearly so well as we can discriminate locations in visual space, but we can still adequately discriminate four different locations.) They showed that immediate probe recall of the sequence at any particular location was substantially more accurate than attempted whole recall of the entire "array." Darwin, Turvey, and Crowder showed that this superiority of probe recall declined with increasing delay of the probe, until at a probe delay of somewhere between two and four seconds probe recall was at the same accuracy level as whole recall.[8]

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[7] U. Neisser, *Cognitive Psychology*. Englewood Cliffs: Prentice-Hall, 1967, pp. 199-218. R. G. Crowder and J. Morton, "Precategorical Acoustic Storage (PAS)." *Perception and Psychophysics*, 1969 (5), 365-73.

Modality

In immediate memory span, where subjects recall a list of about seven items (such as letters or digits) Corballis, Murdock, and others have repeatedly demonstrated that the last two or three items in a list are better remembered when the list was presented auditorially than visually. The items in the earlier positions in the list are sometimes remembered as well, and sometimes remembered better, with visual presentation, so that the only consistently observed advantage of auditory presentation is at the terminal list positions. This has been interpreted to indicate a significant contribution from echoic memory for auditory presentation (and none from iconic memory for visual presentation under these conditions) that lasts for one or two subsequent interfering items (typically anywhere from half a second to a couple of seconds, depending on the rate of presentation).[9]

Interference

The ability to recognize and subsequently remember an auditory stimulus increases according to the amount of time the subject has to attend to the stimulus, up to some limit. This is true when the stimulus is on during the entire study time, but it is also true when the stimulus is on for only a very short time at the beginning, and the increasing study time is time during which the stimulus is off. Massaro presented a tone for 20 milliseconds, varied the blank time following it, then presented an interfering (masking) tone. Subsequent ability to recognize the original tone increased with increasing blank time up to about 200 or 300 milliseconds. During this poststimulus interval, Massaro contends, there must have been an echoic memory trace being processed in order for memory to improve.[10] (Massaro used a nonverbal stimulus, but there is no reason at present to believe that either echoic or iconic memory are different for verbal and nonverbal material.)

Crowder and his colleagues have done a large number of experiments using a similar interference technique to study verbal echoic memory. At a constant retention interval, memory for a list of items is compared to memory for a list of the same length that is followed after a variable delay by a suffix item. The suffix item is known to the subject in advance and is not to be reported; hence it is considered an interference with the supposedly preattentional, echoic components of memory for prior list items. Consistent with this interpretation it is primarily memory of the last item or two that is impaired by the suffix. In further agreement with this interpretation, the greater the physical acoustic similarity (in modality, location, pitch, etc.) of the suffix to the last few list items, the greater the interfering effect, while the semantic similarity has little or no effect. Memory for the last item or two improves with suffix delay, out to anywhere from 2 to 6.4 seconds in different experiments.[11]

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[8] N. Moray, A. Bates, and T. Barnett, "Experiments on the Four-Eared Man." *Journal of the Acoustical Society of America*, 1965 (38), 196-201. C. J. Darwin, M. T. Turvey and R. G. Crowder, "An Auditory Analogue of the Sperling Partial Report Procedure: Evidence for Brief Auditory Storage." *Cognitive Psychology*, 1972 (3), 255-67.

[9] M. C. Corballis, "Rehearsal and Decay in Immediate Recall of Visually and Aurally Presented Items." *Canadian Journal of Psychology*, 1966 (20), 43-51. B. B. Murdock, Jr., "Auditory and Visual Stores in Short-Term Memory." *Acta Psychologica*, 1967 (27), 316-24.

[10] D. W. Massaro, "Perceptual Auditory Images." *Journal of Experimental Psychology*, 1970 (85), 411-17.

Repetition

Treisman presented two separate messages simultaneously to the right and left ears (dichotic listening) with instructions to shadow (repeat back) one message and ignore the other. The messages were identical, but displaced in time, with either the attended or the nonattended message leading in time. Subjects recognized the identity of the two messages at a maximum lag of about four seconds when the attended message led, but at a maximum lag of only about 1.5 seconds when the nonattended message led, which suggests a duration of 1.5 seconds for echoic memory under these conditions.[12]

In a somewhat similar single-channel experiment, Guttman and Julesz tested the ability to detect repeating segments of random (white) noise. The longest segment that could be recognized was slightly less than one second. Here the involvement of higher conceptual levels of memory was presumably excluded by the absence of any conceptual codes for random noise.[13]

Note that estimates of the duration of echoic memory have varied from 200 milliseconds to 6.4 seconds. This variation is not surprising. There is no reason to expect a constant duration for echoic memory any more than for iconic or any other kind of memory. The conditions that presumably affect the duration of echoic memory—the intensity and duration of the stimulus to be remembered and the intensity, duration, and physical similarity of subsequently presented stimuli—are analogous to those that affect the duration of iconic memory.

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[11] Crowder and Morton, "Precategorical Acoustic Storage." R. G. Crowder and V. P. Raeburn, "The Stimulus Suffix Effect with Reversed Speech." *Journal of Verbal Learning and Verbal Behavior*, 1970 (9), 342-45. J. Morton and C. M. Holloway, "Absence of a Cross-Modal 'Suffix Effect' in Short-Term Memory." *Quarterly Journal of Experimental Psychology*, 1970 (22), 167-76. R. C. Crowder and H. A. Prussin, "Experiments with the Stimulus Suffix Effect." *Journal of Experimental Psychology Monographs*, 1971 (91), 169-90. D. A. Routh and J. T. Mayes, "On Consolidation and the Potency of Delayed Stimulus Suffixes." *Quarterly Journal of Experimental Psychology*, 1974 (26), 472-79.

[12] A. M. Treisman, "Monitoring and Storage of Irrelevant Messages in Selective Attention." *Journal of Verbal Learning and Verbal Behavior*, 1964 (3), 449-59.

[13] N. Guttman and B. Julesz, "The Lower Limits of Auditory Periodicity Analysis." *Journal of the Acoustical Society of America*, 1963 (35), 610.

The juxtaposition of the Guttman and Julesz experiment with the Treisman experiment points up the tendency among many cognitive psychologists to identify preattentional or nonattended memory with lower-level featural or even nonverbal memory. Whether this is a reasonable identification is debatable. It is also debatable whether nonattended echoic memory is basically anything different from a lower strength or less consolidated version of the same type of trace that operates in phonetic short-term memory for attended material. Finally, it is certainly not established that echoic memory is partly or entirely a nonassociative activity trace rather than an associative memory trace. The next two sections consider somewhat longer-lasting graphic and phonetic short-term memory for material that was attended to during initial presentation.

GRAPHIC SHORT-TERM MEMORY

In addition to iconic memory, there is some evidence for higher-level, short-term storage of verbal material in the visual structural levels of the verbal modality. Using a reaction time task, Posner and Keele have demonstrated a visual short-term memory for single letters that lasts for at least 1.5 seconds following presentations of the letter. Subjects were run under two conditions: In the *physical match* condition they had to decide whether two successively presented visual letters were physically identical (saying "yes" to A-A and "no" to A-a, A-B, or A-b). In the *name-match* condition they had to decide whether two successively presented letters had identical names (saying "yes" to A-A or A-a and saying "no" to A-B or A-b). If memory for the first letter was strictly phonetic, the time to say "yes" to A-A in the name-match condition should be identical to the time to say "yes" to A-a. This was found for delays between the two letters of more than 1.5 seconds; however for delays of less than 1.5 seconds the physically identical pair (A-A) yielded a shorter reaction time than the physically different pair with the same name (A-a).[14] This suggests that subjects retain a short-term memory trace for the initial item in some visual modality for about one second under these conditions. This graphic short-term memory does not appear to be iconic memory, since the contrast and illumination levels used by Posner and Keele were inadequate to sustain a persistence of vision for as long a period as 1.5 seconds.

Kroll, Parks, Parkinson, Bieber, and Johnson found considerably longer short-term visual storage of verbal material. Many previous studies had found a preponderance of phonetic encoding in short-term memory for verbal material, even when the material was presented visually. To prevent such phonetic recoding of visually presented verbal material, Kroll and his associates used a technique similar to that previously employed by Munsterberg and Murray: the subject's verbal pronounciation and rehearsal systems were kept busy by the requirement to shadow (repeat back) auditory letters presented at a rate of two per second. While they were shadowing, a letter that they were to remember would be presented either visually or auditorally in a different voice. After a retention interval of one, ten or 25 seconds, filled with shadowing, subjects attempted to recall the letter. At the one-second retention interval, recall was very accurate and almost equally good for visual (96.5 percent) or auditory (96 percent) presentation, suggesting little difference in initial perception, though, auditory letters were forgotten much faster than visual letters (40 percent versus 69 percent correct retention at the 25-second retention interval).[15] This differential susceptibility to the phonetic shadowing task suggests that there is some modality of storage for the visual letters other than the phonetic storage presumed for the auditory letters (an idea reinforced by the finding that intrusion errors for the visual letters did not tend to be phonetically similar to the correct item).

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[14] M. I. Posner and S. W. Keele, "Decay of Visual Information from a Single Letter." *Science,* 1967 (158), 137-39.

The presumably visual or graphic character of the memory for the visual letters was more directly indicated by a recognition memory study modeled after the Posner and Keele name-matching technique. Errors were lower and reaction time faster for physically identical presentation-test pairs (such as A-A) than for physically different, but identical name pairs (A-a). A variety of other evidence supports the conclusion that visual or graphic short-term memory often mediates retention of verbal material under these conditions.[16]

SHORT-TERM PHONETIC MEMORY

When you learned to understand speech, you learned to associate various sequences of phonemes (letter sounds) such as /c/, /a/, /t/ to word or

[15] N. E. A. Kroll, T. Parks, S. Parkinson, S. L. Bieber, and A. L. Johnson, "Short-Term Memory While Shadowing: Recall of Visually and of Aurally Presented Letters." *Journal of Experimental Psychology*, 1970 (85), 220-24. H. Munsterberg, "Die Association Successiver Vorstellungen." *Zeitschrift für Psychologie*. 1890 (1), 99-107. D. J. Murray, "The Role of Speech Responses in Short-Term Memory." *Canadian Journal of Psychology*, 1967 (21), 263-76.

[16] T. E. Parks, N. E. A. Kroll, P. M. Salzberg, and S. R. Parkinson, "Persistence of Visual Memory as Indicated by Decision Time in a Matching Task." *Journal of Experimental Psychology*, 1972 (92), 437-38. N. E. A. Kroll, "Visual Short-Term Memory," in Deutsch and Deutsch, *Short-Term Memory*, pp. 153-79.

concept nodes such as *cat* (and to the visual images of the referents for concrete words). When you learned to speak, you developed strong associations in the other direction—from words or concepts such as *cat* to the sequence of phonemes (/c/, /a/, /t/) that must be pronounced to utter the word. Barring serious insult to the relevant part of the brain, these phonetic associations are long-term memories that last for a lifetime. In addition to long-term phonetic associations, there appear to be phonetic memory traces that last for only a few seconds or tens of seconds. These are the short-term memory traces that mediate performance in memory span tasks and allow you to remember a telephone number long enough to dial it after hearing it or looking it up in the telephone book.

Chunking

The average college student can recall about seven digits in order on an immediate memory span test. As an experiment, have a friend read lists of five, six, seven, eight or nine digits at about one digit per second. Find out at what list length you are able to repeat back the entire list correctly about 50 percent of the time. This is your immediate memory span for random digits. Now find a friend who knows the names of the digits in a language you do not know, and do the same experiment (preferably using different digit lists). Your memory span will now be much lower—perhaps only three or four digits, even making generous allowances for your mispronunciations in recall. Why is there this enormous difference in immediate memory? One plausible explanation is provided by the chunking mechanism: As a result of past experience you have formed a unitary chunk node to represent the mass of phonetic information comprising each familiar digit name. If immediate memory span is limited to a constant number of chunks that is roughly independent of the amount of information in each chunk, as George Miller proposed, then you will remember more total information when you have previously formed chunk nodes representing combinations of stimulus attributes.[17] The chunk nodes you use in the familiar language are usually entire digit names, but in the unfamiliar language they may be a mixture of phonemes and syllables (and that's allowing subjects to mispronounce by using closest English approximations).

Would you like to double your immediate memory span? You can probably do it, if you are willing to learn 100 associations. Form an association from every two-digit number to a single word. Use already familiar associations to help you: 65 is "quit" (for retirement age), 00 is "start," 99 is "end," 49 is "gold" (I think of 1849 as the start of the California gold rush), 50 is "half," 76 is "spirit," 98 is "beer" (you already have a good mnemonic for

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[17] G. A. Miller, "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information." *Psychological Review*, 1956 (63), 81-97.

99, so think of starting with 98 bottles of beer on the wall), and so on. It is a bit of work to think up 100 such mnemonics for two-digit numbers and then to practice with them until you have the associations well learned, but if you form the new chunks you can almost double your memory span for digits. (It will not do you much good, except to show off, but it does provide a further illustration of the very important chunking capacity of human memory.)

A less trivial example is that while the memory span for random words is about five, the memory span for words in sentences is about triple that.[18] This can be explained by the hypothesis that we are familiar with many of the phrases in sentences and have unitary chunk nodes for them. It is probably very important to ordinary understanding of speech and writing that we are able to chunk phrases into units and thereby encompass longer passages in our span of immediate memory. Similarly, our ability to speak integrated longer utterances may depend on our being able to plan utterances using entire phrases as units.

The role of chunking in short-term memory has a practical application in the area of man-machine communications, the most familiar being telephone numbers. After you live in a place for awhile, you become pretty familiar with most of the prefix codes for your area. Even though the prefixes are all digits, (342, 345, 686), many of them become single chunks for you. Accordingly, Shepard and Sheenan reasoned, it ought to be better for people to dial the last four digits of an unfamiliar telephone number *first* and *then* dial the familiar prefix. This way the most easily forgotten four chunks get dialed when the memory trace for them is the strongest, and retrieval of the last (fifth) chunk takes place after dialing the fourth digit. Shepard and Sheenan found that there was a 20 percent reduction in dialing time and a 50 percent reduction in dialing errors with this prefix-last method.[19] (This research was done at the Bell Telephone Laboratories; unfortunately we are not likely to see this method adopted in the near future because of the great expense involved in switching equipment, but hopefully human engineers will keep this in mind when they are designing new systems for man-machine communication.)

Phonetic Coding

The importance of chunking in short-term memory indicates that short-term memory traces often involve units at the word, concept, and phrase levels. However, verbal short-term memory traces at lower phonetic levels also appear to play a role. A classic study by Conrad demonstrated that intrusion errors in memory span tasks tended to be phonetically similar to the correct items. For example, if in recalling a letter sequence such as T M B F S P one substitutes another letter for B, the substitution is likely to be another letter containing the /ē/ sound (C, P, T, etc.). Similarly, if one makes an intrusion error for the F, it is likely to be another letter containing the /ĕ/ sound (M, N, S, etc.).[20] Similarly, memory for /ē/ letters is interfered with more by processing other /ē/ letters than by processing letters that are phonetically less similar.[21] The phonetic nature of errors in short-term memory and the importance of phonetic similarity to the magnitude of retroactive interference have been demonstrated repeatedly for a wide variety of verbal materials including letters, numbers, nonsense materials, and words.

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[18] M. R. Marks and O. Jack, "Verbal Context and Memory Span for Meaningful Material." *American Journal of Psychology*, 1952 (65), 298-300.

[19] R. N. Shepard and M. M. Sheenan, "Immediate Recall of Numbers Containing a Familiar Prefix or Postfix." *Perceptual and Motor Skills*, 1963 (21), 263-73.

Most demonstrations of phonetic encoding in short-term memory have focused on the segmental level, as in the demonstration that intrusion errors tend to share phonemes with the correct items, but a number of demonstrations have shown that intrusions for single vowel or consonant segments tend to be similar in phonetic features (voicing, nasality, openness of vocal tract, etc.) as well.[22] In a sequence of consonants paired with a common vowel, such as KA, TA, BA, SA, DA, LA, an intrusion error at a particular consonant position will tend to be similar in phonetic features to the correct consonant at that position. There has been considerable debate concerning whether phonetic short-term memory is auditory, articulatory, or abstract-cognitive (common phonetic nodes for speech recognition and articulation). At present there is no resolution of this matter.[23] In any event, it would appear that the phonetic levels of the verbal modality have both long-term memory and short-term memory.

Phonetic Short-Term Memory Is Partly Associative

The memory span test has been around for a very long time, but psychologists did not begin to study short-term memory extensively until the middle 1950s. It was probably no coincidence that this research accompanied the introduction of high-speed digital computers. In addition to larger long-term storage, computer systems use small-capacity buffer storage for short-term information that needs to be rapidly accessed. Such buffer storage is nonassociative, consisting of a small ordered set of locations in which information can be stored. When they began studying short-term memory in the 1950s, most psychologists appeared to assume, explicitly or implicitly, that human short-term memory was a nonassociative buffer store, and many still accept this assumption, according to which the capacity to repeat about seven digits on a memory span test comes because humans have a buffer store with seven locations, each of which can hold one chunk (item) of information.

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[20] R. Conrad, "Acoustic Confusions in Immediate Memory." *British Journal of Psychology*, 1964 (55), 75-84.

[21] W. A. Wickelgren, "Acoustic Similarity and Retroactive Interference in Short-Term Memory." *Journal of Verbal Learning and Verbal Behavior*, 1965 (4), 53-61.

[22] W. A. Wickelgren, "Distinctive Features and Errors in Short-Term Memory for English Vowels." *Journal of the Acoustical Society of America*, 1965 (38), 583-88. W. A. Wickelgren, "Distinctive Features and Errors in Short-Term Memory for English Consonants." *Journal of the Acoustical Society of America*, 1966 (39), 388-98.

[23] W. A. Wickelgren, "Auditory or Articulatory Coding in Verbal Short-Term Memory." *Psychological Review*, 1969 (76), 232-35.

The small capacity of verbal short-term memory certainly permits the use of a nonassociative memory, since a serial search of up to seven locations would not take an inordinate amount of time. However, there are much data to support the idea that verbal short-term memory has a strong associative component.

Item versus order memory. In short-term memory for a list of consonant-vowel (CV) bigrams such as NA FO JI, under certain conditions there is an experimental demonstration of a dissociation of item and order memory, which is exactly as one would expect with an associative memory. The task is to remember only the initial consonants from a list of CV bigrams, and the two conditions being compared are a homogeneous vowel condition (NA FA JA . . .) and a heterogeneous vowel condition (NA FO JI . . .). When we consider the associative encoding at a segmental phonetic level, the encoding of each CV item consists of two parts, one corresponding to the consonant and one to the vowel. When we just consider the intra-item associations between the consonant and vowel parts and the direct forward inter-item associations between the consonant and vowel parts of adjacent CV items, we obtain the structure shown in Figure 8-4. Addition of backward or remote associations in no way changes the argument; it simply makes the diagram more complicated.

The important fact to be gained from examining the connecting structures for the letters in Figure 8-4 is how much better replicated is memory for the correct order in the heterogeneous vowel condition, since there are four associations connecting each adjacent CV item. By contrast, in the

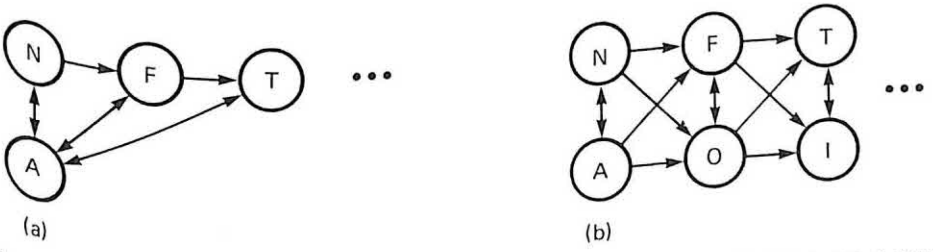


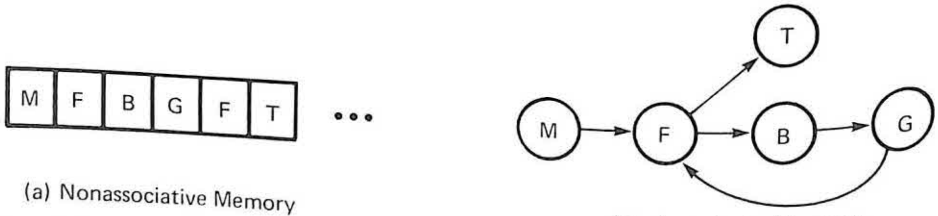
Figure 8-4. Intra-item and direct forward item-to-item associations for a homogeneous vowel CV list (a) and a heterogeneous vowel list (b).

homogeneous vowel condition, only one association, that between adjacent consonants, encodes the order of the items in the list. To the extent that item-to-item associations play a role in short-term memory for such material, one would expect the order of consonants to be far better remembered in the heterogeneous than in the homogeneous vowel condition, and indeed it is.[24]

In an associative memory, recall of the individual consonant items irrespective of order might well be superior in the homogeneous vowel condition, since the vowel is sure to be remembered and it has strong intra-item associations with each of the consonants in the list. This superiority of item recall for homogeneous lists was also demonstrated in the same experiment in which the heterogeneous lists showed superior retention of order information. In this case the retention of order information was tested independently of item information by scoring for correct order only those items that had been recalled correctly irrespective of order. (It might be noted in passing that item-to-item associations appear to play a substantially greater role in short-term memory for rapidly presented lists than they do in longer-term serial learning, where the list is repeated many times at a generally slower rate.)

Since item memory and order memory are generally positively correlated, predicting the dissociation of item and order information is a considerable tour de force for the associative memory theory. It is very difficult to imagine how a nonassociative memory could predict this.

Repeated items. In an associative memory, the connecting structure of associations between item representatives will be rather different for lists containing repeated items than for lists without repeated items. A nonassociative memory predicts no difference between the connecting structure of lists with repeated items and those without repeated items. An example of the difference in the encoding of a list with a repeated item for the associative and nonassociative theories is shown in Figure 8-5.



(a) Nonassociative Memory

(b) Associative Memory

Figure 8-5. The connecting structure for a list with a repeated item (F) in an associative and a nonassociative memory.

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[24] W. A. Wickelgren, "Short-Term Memory for Phonemically Similar Lists." *American Journal of Psychology*, 1965 (78), 567-74.

Experiments comparing short-term memory for lists with and without repeated items have demonstrated a large number of differences that are entirely consistent with the associative memory assumption. The easiest such finding to describe and interpret is the associative intrusion phenomenon. Lists having the form . . . AB . . . AD . . . show a far greater frequency of B intruding in the place of D or D in the place of B than do lists of the form . . . AB . . . CD . . . .[25] Of course, serial position is an important cue in short-term memory for such lists, and this provides a means for reducing the frequency of such intrusions far below 50 percent as might be expected on the basis of item-to-item associations alone. However, the prior item does appear to be an important cue in verbal short-term memory, and there would appear to be no parsimonious way in which a purely nonassociative memory could account for repeated item phenomena such as associative intrusions.

Grouping. The serial position cues that subjects use to encode a list do not appear to be simply the numbers 1, 2, 3, 4, 5 . . . *N*. Rather, subjects typically break a list into groups and use concepts such as the beginning, middle, and end group and the beginning, middle, and end position within a group—that is, they use a cross-classification of serial position concepts corresponding to two levels of encoding: the order of groups and the order of positions within a group.[26]

It is not at all obvious with a nonassociative memory why a subject should resort to such elaborate grouping schemes, if the serial order of items could be easily encoded by stuffing adjacent items into adjacent locations. Such a use of grouping is very functional, though, for an associative memory. If we assume that the number of serial position concepts is sharply limited for most subjects (mnemonists may possess a considerably greater number), then multilayered usage of these position concepts is necessary to encode the positions of the different items in the list uniquely. (It is not at all clear why that number should be on the order of three, as it appears to be, since we clearly have many more number concepts, but this is not really relevant to the present discussion.)

It is important to distinguish a cross-classification scheme from a hierarchy. In an *hierarchical* encoding of serial position, the classification into groups is primary and the classification by position within a group is secondary. The order of items within any group must be preserved by an adequate hierarchical memory, but this memory for the order or relative position within a group is not directly accessible by itself without first accessing the group. With such an hierarchical memory one could not know that an item had been in the first position within its group unless one first knew the group that it was in. With a *cross-classification* memory, information concerning either the group membership of an item or its position within a group could be retrieved independently. These are extreme definitions. Intermediate types of memory are possible, but the extremes serve to communicate the basic distinction. Illustrations of the basic connecting structures of an hierarchical and a cross-classification memory are shown in Figures 8-6 and 8-7.

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[25] W. A. Wickelgren, "Short-Term Memory for Repeated and Non Repeated Items." *Quarterly Journal of Experimental Psychology*, 1965 (17), 14-25. W. A. Wickelgren, "Associative Intrusions in Short-Term Recall." *Journal of Experimental Psychology*, 1966 (72), 853-58.

[26] W. A. Wickelgren, "Size of Rehearsal Group and Short-Term Memory." *Journal of Experimental Psychology*, 1964 (68), 413-19. W. A. Wickelgren, "Rehearsal Grouping and Hierarchical Organization of Serial Position Cues in Short-Term Memory." *Quarterly Journal of Experimental Psychology*, 1967 (19), 97-102.

Many psychologists have assumed that grouping three items is equivalent to combining them into a single chunk. In a nonassociative memory, this permits the subject to economize on the number of memory locations by stuffing three items into one location. If the associative encoding of grouped lists were by means of a simple hierarchy, it might be rather difficult to distinguish such a theory from the nonassociative theory with chunking. However, when grouping has been explicitly manipulated by means of instructions to the subject to rehearse in groups of different sizes, some interesting error results have been observed. Not too surprisingly, the frequency of transposing items within a group is greater than the frequency of intrusions between the same positions when the grouping method causes these positions to fall into different groups.[27] What is much more difficult for a nonassociative chunking theory or for a simple hierarchical associative theory to explain is the fact that intrusion frequencies are also elevated for comparable positions in different groups. That is, when an error is made in a certain position, it is much more likely than chance to be an item from the same position in a different group. Such findings suggest a cross-classification scheme for associative memory in which both the group serial position concepts and the within-group serial position

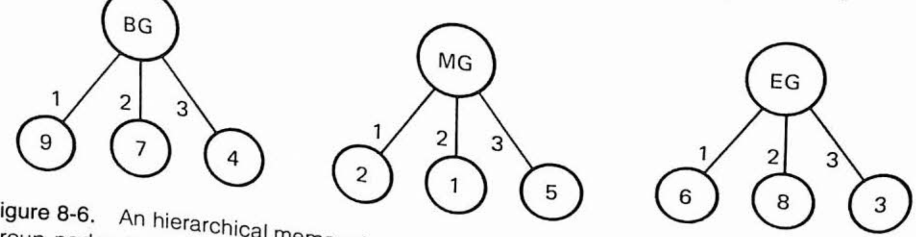

Figure 8-6. An hierarchical memory for the grouped list 974 215 683. Note that the links from group nodes to the digit nodes might be labeled in some way to help preserve all the order information (in addition to item-to-item links). However, in an extreme version of an hierarchical memory, this information concerning the secondary dimension of position-within-a-group is not retrievable unless the group membership links are intact.

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[27] *Ibid.*

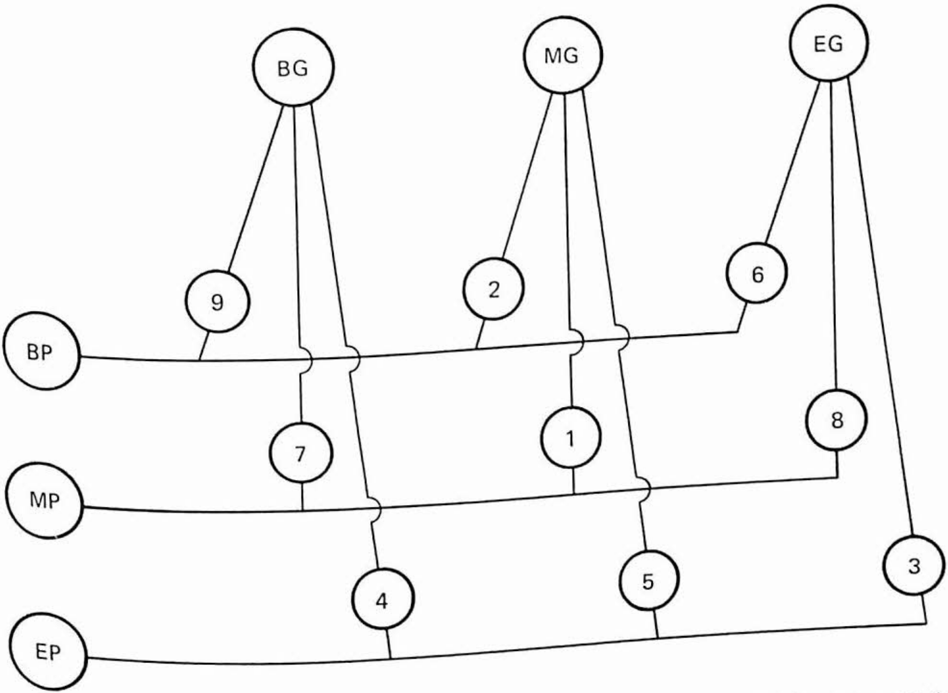

Figure 8-7. A cross-classification memory for the group list 974 215 683. The group or the position information about an item can be retrieved independently.

concepts are at least semi-independently associated to each item in the list.

These results simultaneously contradict the nonassociative theory and provide evidence that grouping should not always be considered equivalent to chunking. Sometimes grouping is simply a multilayered (in this case a cross-classification) system of serial position concepts to aid in the associative encoding of a list. As we discussed in Chapter 1, chunking is the formation of a new node to stand for a conjunction of other nodes. In some cases grouping may be accompanied by chunking, but these concepts are not equivalent, and grouping does not always imply chunking.

SUMMARY

1. Coding refers to the representation of events and concepts in the nervous system (what is learned), including understanding the different modalities of the mind, the different levels of a modality, and the associative versus nonassociative character of memories within or between levels of a modality.
2. The most peripheral levels of the verbal modality are the visual and the auditory sensory feature levels. Memory at these levels is termed iconic (for visual features) and echoic (for auditory features). Iconic

and echoic memory are often considered undifferentiated for verbal and nonverbal memory.

3. Iconic memory includes both persistence of vision and afterimages.
4. Iconic memory fades within 0.2 of a second under ordinary light adapted conditions, but it can last for several seconds under dark adapted conditions. Negative afterimages following intense and prolonged visual stimulation can last for tens of seconds.
5. Iconic memory is nonassociative: A pattern of stimulation is impressed upon each storage location in a two- or three-dimensional array, and this pattern persists for a time after the stimulus ceases.
6. Iconic memory probably has a retinal locus.
7. Echoic memory refers to persistence of audition.
8. It appears to persist for anywhere from 0.2 of a second to several seconds under different conditions, a time range comparable to iconic memory.
9. The locus and associativity or nonassociativity of echoic memory are unknown.
10. Some visual (graphic) short-term memory traces outlast and are different from iconic memory.
11. Phonetic short-term memory that can last many seconds contributes to our ability to repeat back sequences of about seven items, dial telephone numbers, etc. We know that part of this memory uses a phonetic code because errors are phonetically similar to the correct items.
12. Verbal short-term memory is not limited to the phonetic level, but extends to the word, concept, and phrase levels. We know this because short-term memory span can include many more phonetic attributes (segments or features) when these phonetic attributes form familiar chunks. Memory span is limited to an approximately constant number of chunks, independent of the number of attributes in each chunk.
13. Phonetic short-term memory is at least partly associative, and item-to-item associations and position-to-item associations both play important roles in immediate memory for serial lists.
14. Grouping often refers to the use of a cross-classification by two levels of serial position cues (beginning, middle, and end groups and beginning, middle, and end positions within a group). Grouping is therefore a distinct concept from chunking (which refers to defining a new node to stand for a combination of old nodes).

9 Verbal Learning and Long-Term Memory

OBJECTIVES

1. To distinguish the following logical types of memory: (1) memory for items, order, and associations (pairings) of items; (2) attributes of memory such as recency of events, frequency of events, spacing between events, duration of an event, and modality of presentation; (3) rote memory versus inferential memory; and (4) semantic memory for general principles versus episodic memory for particular events.
2. To describe a number of basic learning and memory phenomena that support the hypothesis that long-term conceptual memory is associative. These phenomena include rapid access to a memory of very large capacity, limited accuracy of recency judgments, transfer between serial and paired associate learning, similarity effects in interference, whole versus part learning, organization in free recall, and spacing judgments.
3. To describe a number of learning and memory phenomena that illustrate chunking, which may be an essential component of concept learning. Chunking points up the probable importance of vertical (horizontal) associations as opposed to the older conception of horizontal associations in memory.
4. To distinguish types of associations such as forward, backward, remote, implies, or coimplies associations.

LOGICAL TYPES OF MEMORY

The first section of this chapter surveys a number of distinctions between logically different types of memory, beyond the modality and level distinctions. Whether these logical distinctions correspond to significant psychological distinctions remains to be seen, but they are useful to consider.

Item, Order, and Association Memory

You have a number of errands to run: going to the bank, picking up clothes at the cleaners, filling a prescription at a drugstore, picking up your children at school, stopping by a friend's house to drop something off, going to the bakery, and getting an number of items at the supermarket that you need for dinner tonight. In the interests of saving both gas and time, you arrange these errands into an efficient ordering. Since it is difficult to remember this many things, you write them all down in the order the errands are to be performed. After leaving the house, and driving a half mile or so, you realize that you have forgotten your list. No one ever likes to go back, so you attempt to remember everything you wrote on your list.

Three types of memory are illustrated in this situation. First, there is *item* memory. To the extent that you can remember all the different errands on the list, you have remembered all the items. Second, there is memory for the *order* in which the errands were to be performed. Third, remembering all the items that were to be purchased at the supermarket illustrates *association* memory to the extent that one item is associated with other items, with what you plan to cook for dinner, etc. In this case, item memory will be facilitated by order and association memory. Also, memory of the order of errands on the list may be partially mediated by associations between errands that follow one another. Finally, you may remember the items you are intending to purchase at the supermarket because of your memory for the order in which you wrote them down on your list even though this ordering was functionally irrelevant. Hence, what appears to be a reasonably neat logical distinction between item, order, and association memory is not necessarily paralleled by a neat separation of the psychological processes involved.

Psychologists have attempted to study these three types of memory via experimental paradigms that provide somewhat tighter control. For example, in *paired-associate* learning subjects see pairs of items and are tested for recall of the "response" item given the "stimulus" item. The same items are presented together as a pair on each trial, but the pairs are presented in a different order, so that there is no possible mediation of association memory by means of memory for the serial position of the items. There is still a potential contribution from item memory for the "responses," but this can be controlled by changing the retrieval task to recognition memory for pairs. In such paired-associate recognition memory, the subject can be guaranteed that both items have been presented, and the only task is to decide whether the two items have been presented together as a pair. Such a procedure would appear to logically exclude any contribution from item or order memory.

If a subject is asked to recognize whether an item was presented previously in a list and required to answer in less than one second following presentation of the stimulus, it is likely that there is not enough time to recall any associated material, so that such an *item recognition* task might be considered a pure test of item memory without contribution from association or order memory.

Order memory can be studied independently of item memory by procedures similar to the one used to study association memory: subjects are given a pair of items that are guaranteed to be in the same *serial list* and asked to judge whether the second item followed the first. In the case of adjacent items in a serial list, there would appear to be no way to exclude a potential contribution from association memory, and indeed order memory may be based in part on associations between adjacent items.

The ability to define rigorous logical and experimental distinctions between types of memory does not imply that these different types are mediated by fundamentally different psychological mechanisms. In particular, there is no reason to assume that the information is stored in different parts of the brain or that the properties of the memory traces that mediate each are different in any way. So far there has been no convincing demonstration that this rather basic logical difference is paralleled by any important psychological difference. It will be argued later in this chapter that all three types of memory are mediated by the formation or strengthening of associations, though of course what is associated is somewhat different for item, order, and association memory.

Attributes of Memory

A number of psychologists, most notably Hintzman, Underwood, Wickens, and Yntema, have drawn attention to the fact that a very large number of logically different types of memory are established by the occurrence of a series of events (presentation of a set of items). Besides remembering items, order, and associations, we can judge the *recency* with which an event occurred, its *frequency* in some context, the *spacing* between two previous occurrences, the *duration* of an event, and attributes related to *modality* of presentation (visual versus auditory presentation, printing in capitals versus small letters, color of print, etc.).[1] With the possible exception of recency, there are reasons to believe that all these attributes of memory are mediated by the same type of associative memory by which we remember any other kind of information.

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[1] B. J. Underwood, "Attributes of Memory." *Psychological Review,* 1969 (76), 559-73. D. D. Wickens, "MPA Symposium on Coding Processes in Human Memory." *Memory and Cognition,* 1973 (1), 485-90. D. L. Hintzman, "Apparent Frequency as a Function of Frequency and the Spacing of Repetitions." *Journal of Experimental Psychology,* 1969 (80), 139-45. D. L. Hintzman, "Effects of Repetition and Exposure Duration on Memory." *Journal of Experimental Psychology,* 1970 (83), 435-44. D. L. Hintzman, J. J. Summers, and R. A. Block, "Spacing Judgments as an Index of Study-Phase Retrieval." *Journal of Experimental Psychology: Human Learning & Memory,* 1975 (104), 31-40.

Memory for the frequency, spacing, duration, modality, and other specific attributes are typically considered less relevant by the subject than conceptual memory for events. When psychologists have investigated memory for these irrelevant attributes, they have frequently used *incidental learning* paradigms. That is, the subject is not told at the time of exposure to the events that memory will be tested for these attributes. It is reasonable to imagine that under such conditions subjects pay less attention to these attributes than to the more dominant conceptual (semantic) attributes. Although both the attributes and the learning paradigms are different, there is no reason to think that irrelevant attribute memory for frequency, spacing, duration, and the rest is based on some entirely different process from that which mediates conceptual memory. It is reasonable to assume that subjects form a number of memory traces at the time any event is presented, such as remembering the proposition that "This is the second time that this item has been presented," "It was presented about two minutes ago." "The last time it was presented visually, but this time it is being presented auditorally," and so on. As we shall discuss later in this chapter, we can remember the spacing between occurrences of two *equivalent* events (for example two repetitions of the same word) at above-chance accuracy under conditions where the ability to judge the spacing between two *different* items is no better than chance. This is strongly consistent with the notion that spacing judgments are mediated by formation of an association at the time of the second presentation of an item, which simply does not occur between pairs of different events.

Many recency judgments are also mediated, directly or indirectly, by associations with time concepts (year, month, day, hour). For example, you may remember rather exactly the time that you left for school or work on a particular morning, provided you looked at your watch at about the time you left. Memory for the time of day at which you perform some act under such circumstances is very likely associative, on a par with any other kind of memory. You can use this information in conjunction with knowledge of the current time of day to allow you to judge rather accurately the recency of an event. On a larger time scale you can judge how long ago you graduated from high school, since you probably remember the month and year.

However, there are many conditions under which there would appear to be no conceivable mediation of recency judgments via direct or indirect associations with time concepts. You begin talking to a friend but you do not look at your watch, and later you estimate how long you have been talking. Such a judgment will be far above chance, even though there is no conceivable mediation via direct or indirect associations with time concepts.

There are several different theories about the ability to make such recency judgments. Ornstein and others think that this recency memory is mediated by judging the number of memory traces that have been formed or that can be retrieved during the period of time being judged.[2] If we stored or can retrieve many memories for some time period, we judge it to be a long time. There is some evidence supporting Ornstein's storage size hypothesis, and it is plausible to imagine that a complex reconstructive process of this type might sometimes be of value in judging durations. However we can also have a direct impression of the recency of events without any conscious assessment of the number of memory traces established over a period of time. There are at least two different "biological clock" theories that postulate more direct mechanisms for recency judgments. According to one of these theories, every event has a time tag attached to it when it is stored in memory, and this time tag might be associated with the event. When the memory is retrieved, the time tag can also be retrieved and compared with the current value of one's internal clock.[3]

According to another theory, every memory trace has two properties, *strength* and *fragility*. At the time a memory trace is established, strength and fragility both have initial values, and both decline progressively over time. Recency judgments are based on trace fragility, while other memory judgments are based on strength. The greater the fragility, the more recently an event occurred.[4]

Reproductive versus Reconstructive Memory

Reproductive memory is memory of material that has been directly stored and does not require any inferential combination of information stored in memory. *Reconstructive memory* involves drawing conclusions as to what might have happened or what must be true, based on what one can remember. Some psychologists believe it is important to distinguish between these two types of memory on theoretical grounds, though there is no direct evidence to support such a distinction.

Until recently most psychologists have concentrated upon reproductive (rote) memory, though Bartlett, Dawes, and a few others have worked on memory for prose.[5] Recently, however, psychologists have been studying more complex semantic memory in a manner that includes inferences as a natural part of the retrieval process. This is important, because most of the questions that we can answer require inferential combinations of several different associations. For example, I know that people live in Canton

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[2] R. W. Ornstein, *On the Experience of Time*. Baltimore: Penguin, 1970.

[3] D. B. Yntema and F. P. Trask, "Recall as a Search Process." *Journal of Verbal Learning and Verbal Behavior*, 1963 (2), 65-74.

[4] W. A. Wickelgren, "Single-Trace Fragility Theory of Memory Dynamics." *Memory and Cognition*, 1974 (2), 775-80.

[5] F. C. Bartlett, *Remembering: A Study in Experimental and Social Psychology*. London: Cambridge University Press, 1932. R. M. Dawes, "Memory and Distortion of Meaningful Written Material." *British Journal of Psychology*, 1966 (57), 77-86.

China, even though I probably never directly stored this information, because I know that Canton is a city and cities generally have people living in them. The number of questions we can answer through this inferential combination of direct associations far exceeds the number we can answer on the basis of direct associations alone.

Memory based on inferences is ubiquitous even for events whose aspects might have been stored directly. We habitually infer what must have happened based on the fragments that we can directly recall concerning an event. Furthermore, we do this in a way that is often rather hard to distinguish from direct associative recall. Since human inference is far from infallible, the difficulty in distinguishing reproductive from reconstructive memory can sometimes be a serious problem, as in court room testimony by eye witnesses to accidents or crimes. Unless a lawyer carefully questions and cross-examines them, eye witnesses will frequently recall a large number of details that are based not on direct perception and memory, but rather on inferences, some of which may be incorrect. Many of these inferences occur as a part of the perceptual process; others occur during retrieval.

Clearly, inferential or reconstructive memory is very important and its neglect a serious omission. Nevertheless there is still every reason to believe that principles derived from more elementary reproductive memory tasks also apply to the direct associative component of inferential memory.

Semantic versus Episodic Memory

Tulving has introduced a distinction between semantic and episodic memory. Semantic memory refers to impersonal memory for concepts and principles, especially the grammar and word-meanings of language. (This more general use of the term semantic to include knowledge of the syntax (grammar) of language as well as of word, phrase, and sentence meaning is a new trend in psycholinguistics based on the assumption of a closer relationship between syntax and semantics in the narrower sense.) Episodic memory is for the specific personal events that have occurred in our lives, and usually includes a specific time and place.[6] These two types of memory do appear to be functionally differentiated to some extent, in that we generally do not remember the specific contexts in which we learn concepts, facts, or principles. For example, I do not remember the context in which I learned that planets revolve around a sun or that *generic* means "pertaining to general classes of things."

However, there are cases in which we can remember the specific contexts in which semantic knowledge was obtained, and it is easy to explain the fact that we typically do not remember this contextual information. The semantic information that we are able to remember has typically been presented and remembered in a wide variety of different contexts. This means that a semantic fact *A* has been associated with many contexts—*B, C, D,* etc. As will be discussed in the next section of this chapter and in Chapter 14, the establishment of two or more associations to the same stimulus (*AB, AC, AD,* etc.) causes interference in the memory for any one of these associations. This associative interference process explains why we don't remember any particular context in which semantic information was learned without having to assume separate memory systems for semantic and episodic information.

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[6] E. Tulving, "Episodic and Semantic Memory," in E. Tulving and W. Donaldson (eds.), *Organization of Memory.* New York: Academic Press, 1972.

LONG-TERM CONCEPTUAL MEMORY IS ASSOCIATIVE

You are walking to your final exam in sociology, and you ask yourself, "What do I know about sociology?" For what seems like an eternity, nothing comes to mind, and then gradually you recall a few scattered bits of knowledge. You panic! You think to yourself, "I have studied hard for this course. My mind should be filled with knowledge of sociology. How come so little comes to mind?" Relax. You have merely demonstrated that conceptual memory is associative. The little test you gave yourself is virtually irrelevant to assessing your knowledge of sociology, because your knowledge of sociology is not in a set of file folders under a heading that you can look into and scan over. Such a memory would be of much less value than the associative memory you have.

Your memory stores associations to specific cues. You just gave your associative memory the wrong sort of cue, a cue so nonspecific to a large body of knowledge that little in particular emerged in response to that cue. Of course in time you can generate specific concepts and propositions in sociology that will serve as cues for further retrieval, but there is nothing surprising in your getting off to such a slow start.

Now let's consider specific arguments for the associative character of long-term conceptual memory. The purposes of this section are to provide more detailed understanding of the theory of associative memory and to present some interesting phenomena that can be remembered in a more unified way within the framework provided by this theory.

Capacity

How many concepts and propositions are stored in our long-term memory that are retrievable via the proper cues? No one has a very accurate estimate, but there must be tens of millions or more. The vocabularies of many people are estimated at tens or hundreds of thousands of words by themselves. When one considers the different combinations of concepts associated with these words that compose the various propositions (facts and principles) that we have stored in our memories, the size of long-term conceptual memory is staggering. To retrieve a proposition from a nonassociative storage system for such a large body of material using a serial search process would require an enormous amount of time (with any reasonable estimate of the search time per location). Long-term conceptual memory must rely on some direct-access retrieval system with little or no searching.

Recency Judgments

Perhaps the principal advantage of a tape recorder memory over associative memory is its capacity for extremely precise temporal resolution. Once an event has been located on such a tape, one ought to be able to make very precise recency judgments, and one certainly should be able to judge the relative recency of two events with high accuracy, assuming each event is still stored on the tape. In fact, there is little reason to expect temporal order judgments for two well-remembered events to ever be confused in such a nonassociative memory. It is true that with a tape recorder memory the representatives of events can decay or be erased or covered over with noise, but such a memory would not be expected to interchange the order of event representatives.

Human beings do have some capacity for making relative recency judgments, but it is abysmally small in comparison to what could be achieved by someone with a tape recorder memory. We are frequently able to remember two facts perfectly well, but we have little or no ability to remember which fact was learned more recently. As previously discussed, the capacity we do have for making temporal judgments of the order of events appears to be far better explained by means of direct or indirect associations to time concepts, possibly supplemented by some sort of intermediate-term (seconds to hours) biological clock.

Transfer between Serial and Paired Associate Learning

The first systematic experimental studies of human learning and memory were performed by the German psychologist Hermann Ebbinghaus in the 1880s.[7] Among his many important contributions to the field, Ebbinghaus invented the method of serial list learning in which the task is to learn in order a series of *N* items (words, nonsense syllables, letters, digits, etc.). For convenience, we can designate the successive elements of the list by *ABCDEF*, etc.

The two most common procedures for serial list learning are the method of *complete* presentation and the method of serial *anticipation*. With the complete method, the entire serial list is presented (usually sequentially at a rate, say, of one item per second), followed by a test of retention, such as having the subject attempt to recite the entire list. One presentation and retention test of the entire list constitutes one trial, and trials follow one after another.

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[7] H. Ebbinghaus, *Memory*. New York: Dover, 1964.

In the anticipation method the subject attempts to recall the first item in the list, followed by presentation of the item, followed by attempted recall of the second item, then presentation of the second item, and so on. A trial is defined as a complete passage through the entire serial list, with a typical rate of presentation being two or four seconds per item, during which time the subject can note the correctness of his previous response and attempt to anticipate the next item. Verbal materials such as letters, numbers, nonsense syllables (CEG, RIZ, etc.), or words are typical materials used as items in serial learning. Presentation can either be auditory or visual, though visual presentation has tended to be favored.

Psychologists once thought that subjects learning a serial list (*ABCDEF* . . .) essentially learned a series of paired associates *AB*, *BC*, *CD*, *DE*, *EF*. If this were so, subjects should show considerable positive transfer in the subsequent learning of a *consistent* list of paired associates: *AB*, *CD*, *DE*, *EF*, . . . That is, they should learn such a paired-associate list must faster than if they had learned a *neutral* list with different items (*MNOPQ* . . .) or an *inconsistent* list (*DAECBF* . . .). It is important to compare the performance of the consistent group with a control group that previously learned a neutral prior serial list to control for general practice effects in list learning. One might also expect negative transfer from a prior inconsistent serial list compared to the neutral control condition, at least under conditions where the *ABCDEF* . . . items themselves were well-learned units such as words. That is to say, subjects might take more trials to learn a paired-associate list when it was preceded by an inconsistent serial list than when it was preceded by a neutral serial list. The same expectations should also hold when the transfer is tested in the opposite direction from paired-associate learning to a consistent, neutral, or inconsistent serial list.

Since nearly identical associations were presumably being learned in both cases, imagine the surprise of psychologists when some experiments showed little or no positive transfer for consistent lists and other experiments showed small though statistically significant transfer effects.[8] The upshot of this area of research is that when many subjects learn when they learn short serial lists are associations of the items with serial position concepts, frequently involving grouping of the items. That is to say, subjects associate serial position concepts such as "first item in the second group of three" with the appropriate item. Item-to-item associations are also formed in serial list learning (particularly in longer lists), but position-to-item associations are often at least as important if not more so.

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[8] R. K. Young, "Serial Learning," in T. R. Dixon and D. L. Horton (eds.), *Verbal Behavior and General Behavior Theory*. Englewood Cliffs: Prentice-Hall, 1968, pp. 122-48.

The assumption that memory for such material is associative can handle such findings, but only by rejecting the naive assumption that the only associations being strengthened are those between representatives of events occurring in the external world. Subjects are assumed to be thinking and quite able to associate these thoughts with each other. We must assume mental association of contiguously activated ideas, not exclusively or even necessarily associations of representatives of contiguous sensory events. Subjects use their memories to supply additional associative structure for the encoding of any particular experience, and they are also paying more attention to some aspects of their experience than to others.

Similarity Effects in Interference

One of the best-established and most fundamental facts concerning human memory is its susceptibility to interference from subsequent (and sometimes prior) learning of similar material. Learning many associations to a common stimulus reduces your ability to recall or recognize any of these associations (except recognition of the last association learned). John Anderson has shown that this applies to memory for meaningful (propositional) material as well as for the paired-associate material so frequently studied in the laboratory.[9]

Since it is easier to describe interference phenomena for paired associates, we use this as our example. When a subject learns an *AB* pair and then an *AD* pair, subsequent attempts to recall either the first or second associate of the *A* item are almost always less successful than recall of the associate of an *A* item when subjects have learned *AB* followed by *CD* or *CD* followed by *AB*.

The negative effect of subsequent learning on the storage or retrieval of prior learning is termed *retroactive interference* (RI). The negative effect of prior learning on the acquisition, storage, or retrieval of subsequent learning is here termed *proactive interference* (PI). The term *negative transfer* is often used to refer to the negative effects of prior learning on subsequent acquisition (learning), and *proactive inhibition* is the label for its negative effects on storage (retention). However, this usage leaves the negative effects of prior learning on the retrieval of subsequent learning in a somewhat ambiguous position. For some purposes it is convenient to have a term such as proactive interference, which is neutral with respect to the phase locus of the negative effect. We shall examine whether the negative effects of proactive or retroactive interference are in acquisition, storage, or retrieval primarily in the chapters concerned with memory dynamics. It is even possible for retroactive interference to have a negative effect on the acquisition phase of prior learning if it shuts off rehearsal more effectively than the control condition. However, careful experimentation usually eliminates the possibility of differential rehearsal.

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[9] J. R. Anderson, "Retrieval of Propositional Information on Long-Term Memory." *Cognitive Psychology,* 1974 (6), 451-74.

Since repeated presentation of the same event often directly accesses the same internal representatives in an associative memory, *AB-AD* paradigms often result in the establishment of two associations with the *A* representative. Clearly, such memories might interfere with each other. In particular, unless auxilary information is stored concerning the relative time of occurrence of each association, an associative memory can lose the information concerning which pair occurred first. Hence, one would expect greater difficulty at the time of retrieval in recalling the first associate of *A* in the *AB-AD* paradigm than in the *AB-CD* paradigm, and such effects are observed. A tape recorder memory need not have this problem.

With recognition tests of whether *AB* was previously presented as a pair, one also observes similarity-dependent retroactive interference. Learning of a subsequent *AD* association appears to weaken the strength in storage of a previously stored (similar) *AB* association. That is, learning *AD* produces some *unlearning* of *AB*. Learning of a subsequent *CD* association produces no greater forgetting than that found in a nonlearning control condition that prevents rehearsal.[10] Since human associative memory must have some limit to its capacity to connect one node to other nodes, such similarity-dependent unlearning is very reasonable. With a tape recorder memory, the ability to retrieve an *AB* pair might decline with an increasing amount of intervening material learned, but there is no necessary reason that either storage or retrieval interference should depend on the nature of the material learned in the retention interval. That is to say, the *AB-AD* and *AB-CD* conditions might both produce poorer recognition of *AB* than the nonlearning *AB*, Rest (with rehearsal control) condition. However, the pattern of results is that *AB-AD* produces interference in recognition memory for *AB*, while *AB-CD* produces no interference at all compared to the nonlearning control condition.

There are now at least 22 studies of recognition memory that demonstrate similarity-dependent unlearning as an associative interference mechanism. In the first such demonstration, McGovern had all subjects learn two lists of paired associates, the stimuli consisting of eight nonsense syllables and the responses being eight words (adjectives)—for example, CED-joyful, MUZ-great. All subjects learned the same first list of paired associates using the method of serial anticipation with a 2:2 second rate on a memory drum. That is to say, the stimulus item of a pair was presented for two seconds, during which the subject was to attempt to recall the response member of the pair, followed by two seconds in which the correct response member was presented simultaneously with the stimulus member. Then there would be a new stimulus item. A learning trial consisted of anticipation testing and feedback regarding the correct response for each of the pairs. Four seconds elapsed between trials, and stimuli were randomly reordered for each trial so that temporal order (serial position) could not serve as a cue to the correct response. All subjects learned the first list to a criterion of one errorless trial—that is, they correctly anticipated all eight responses to the stimuli on a given trial. An average of 9.5 trials were required to reach the criterion on the first list. Following this, subjects were divided into four groups, each learning a second list that differed in its relation to the first list. One group learned a list consisting of the same stimuli used in the first list but with the stimuli paired with new responses (the *AB-AD* paradigm). Another had the same responses but new stimuli (the *AB-CB* paradigm). A third group received the same stimuli and the same responses but with the pairings changed (the *AB* rearranged or *ABr* paradigm). The fourth group received new stimuli and new responses on the second list (the *AB-CD* paradigm). All groups had 15 learning trials on the second list followed by a recognition-matching test for the associations learned on the first list, which consisted of presentation of all eight stimuli and all eight responses from the first list with subjects instructed to match them together.

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[10] For a review and a listing of 22 experimental studies that support these conclusions see W. A. Wickelgren, "Memory Storage Dynamics," in W. K. Estes, *Handbook of Learning and Cognitive Processes*, Vol. 4. Potomac, Md.: Lawrence Erlbaum Associates, 1976, pp. 321-61.

McGovern did not have a Rest control group that performed some nonlearning rehearsal-controlling task during the retention interval, while other groups were learning the second list, but *AB* recognition matching was so close to perfect in the *AB-CD* paradigm (7.83 out of 8 pairs correctly matched) that this Rest control group would have been largely superfluous anyway, since its performance could not have exceeded the *AB-CD* group by any significant amount. In any event, other studies indicate no difference between the *AB-CD* paradigm and the nonlearning (Rest) control condition. However, all of the other conditions demonstrate that learning a second list of similar pairs produces unlearning of the first list of pairs. An average of 6.5 pairs were correctly matched in the *AB-AD* paradigm, 6.9 in the *AB-CB* paradigm, and 5.6 pairs in the *ABr* paradigm. McGovern interpreted these results to indicate that subsequent *AD* learning produces partial unlearning of the forward association from *A* to *B*, while subsequent *CB* learning produces partial unlearning of the backward association from *B* to *A*, and subsequent *ABr* learning produces unlearning of both forward and backward associations between *A* and *B*. She made the further reasonable assumption that a recognition memory test taps the strength of both forward and backward associations so that weakening either association will produce a reduction in correct performance.[11] McGovern's results and those of over 20 other studies support the conclusion that approximately equal unlearning of the bidirectional *AB* association is produced by subsequent *AD* or *CB* learning, with subsequent *ABr* learning producing the greatest unlearning as assessed by a recognition matching test.

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[11] J. B. McGovern, "Extinction of Associations in Four Transfer Paradigms," *Psychological Monographs*, 1964 (78), Whole No. 593, 1-21.

Anderson obtained a rather different demonstration of associative interference, this time in semantic memory for meaningful sentences. First he had subjects learn a data base of 26 sentences of the form "A person is in the location." For example, subjects learned sentences such as "A hippie is in the church" and "A policeman is in the park." In the data base of 26 sentences some persons were paired with only one location and some locations were paired with only one person. Other persons were paired with two or three locations (in different sentences), while other locations were paired with two or three persons. Following learning, Anderson performed a reaction-time experiment to determine how rapidly subjects could verify the truth or falsity of a test proposition of the form "A person is in the location." Some of the test propositions were correct pairings of previously presented persons and locations, others were incorrect pairings. The error rate and the subject's reaction time were measured for all conditions. Reaction time was measured from the projection of the test sentence on the screen to the depression of one of two response buttons corresponding to the judgments that the test sentence was true or false (based on the preceding data base of 26 sentences). There were 18 different conditions in the experiment, representing all the combinations of three different factors: the number of pairings of the test person with different locations in the data base (one, two, or three), the number of pairings of the test location with different persons in the data base (one, two, or three) and whether the pairings were true or false.

Error rate was low in all conditions, averaging around 4 or 5 percent. There was some tendency in the case of the false test sentences for the error rate to increase with greater amounts of associative interference (a greater number of locations associated with the test person or a greater number of persons associated with the test location). However, Anderson's primary interest was in reaction time, and reaction time for both true and false sentences increased systematically and significantly with increases in the amount of associative interference. The results are shown in Table 9-1.[12] This associative interference effect might occur in the storage or the retrieval phases of memory or both. The results demonstrate that semantic recognition memory has the same associative interference effects previously found in studies of rote paired-associate learning.

Whole versus Part Learning

Over the years there has been some interest among learning psycholo-

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[12] Anderson, "Retrieval of Propositional Information."

Table 9-1. Average Reaction Time (sec.) in Anderson's Study

		True sentences Locations per person				*False sentences Locations per person*			
		1	2	3	Average	1	2	3	Average
Persons per location	1	1.18	1.24	1.27	1.23	1.26	1.27	1.32	1.28
	2	1.28	1.25	1.32	1.28	1.34	1.32	1.32	1.33
	3	1.19	1.24	1.51	1.32	1.36	1.39	1.41	1.39
	Average	1.22	1.24	1.37	1.28	1.32	1.33	1.35	1.33

gists in whether the learning of a body of material (usually a serial list) would be superior learned as a whole or part by part.[13] With a nonassociative memory we have two ways of learning a list such as *ABCDEF* in parts *ABC* and *DEF*. The first way is repetition of each part, wherein the tape head might move back over the same three locations, impressing a successively clearer image of *A* in the first location, *B* in the second location, and *C* in the third location. This would be followed by the impression of *D* into the fourth, *E* into the fifth, and *F* into the sixth location. The second way is for the system to use replication (multiple copies) to strengthen the memory via repetition, setting up a structure such as *ABC, ABC, ABC, DEF, DEF, DEF*.

Neither alternative can be squared with the facts. The strengthening alternative, which appears on the surface to be the more reasonable, completely fails to account for the fact that after humans have learned all the parts via the part method, they have considerable difficulty connecting the parts. It is as if the end of one part had to be explicitly associated to the beginning of the next part. This should not be necessary with this kind of nonassociative memory.

The replication alternative has the opposite problem. How does the subject ever learn to connect the parts? If previous part learning is beneficial, as it clearly is, how does the subject ever learn to stop making *CA* errors? The simple linear connection structure of a tape recorder memory is inadequate to account for the more complex network structure of conceptual memory, even in the case of simple linear list learning.

By contrast, the assumption that conceptual memory is associative appears to be consistent with the basic facts of whole versus part learning.

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[13] For a review of early studies, see J. A. McGeoch and A. L. Irion, *The Psychology of Human Learning*, 2nd ed. New York: Longmans, 1952, pp. 499-507. See also: L. Postman and J. Goggin, "Whole vs. Part Learning of Serial Lists as a Function of Meaningfulness and Intralist Similarity." *Journal of Experimental Psychology*, 1964 (68), 140-50. A. L. Fingeret and W. J. Brogden, "Part vs. Whole Practice in the Acquisition of Serial Lists as a Function of Class and Organization of Material." *Journal of Experimental Psychology*, 1970 (83), 406-14.

Although learning of serial lists is frequently superior with the part method, the whole method is sometimes superior in learning efficiency, despite the fact that subjects almost invariably have a strong preference for the part method and they receive more immediate reinforcement in the form of correct performance using the part method. Thus, there would appear to be some learning advantage for the whole method that can under some conditions outweigh the motivational advantages of the part method. With an associative memory, the advantage of the whole method is that it achieves the greatest *efficiency ratio* of associations rehearsed to events rehearsed. Considering only direct (adjacent) forward item-to-item associations for a list of N items learned by the whole method, the number of items rehearsed is N while the number of direct forward associations rehearsed is $N-1$. Thus, the efficiency ratio of learning a list of N items at a time is $(N-1)/N$. With a constant rehearsal rate, the time for repetition of N items is N times the time to rehearse one item. However, in an associative memory, the gain in memory strength depends on the number of adjacent *pairs* rehearsed. This efficiency ratio of associations rehearsed to items rehearsed increases with the length of the list—that is, $(N-1)/N$ gets larger as N gets larger. For example, in learning a list of two items the efficiency ratio is ½, but in learning a list of eight items it is ⅞.

More important, this efficiency ratio is especially unfavorable in connecting the parts, where one direct forward association is being strengthened, but at least two (and typically more) items are rehearsed in order to strengthen that one association. This also agrees with the fact that in learning by the part method a very large amount of time is typically spent learning to connect the parts.

Free Recall

Free recall is an experimental paradigm in which subjects are presented a list of items (typically words) and instructed to recall as many of the items as possible, order being irrelevant. From the standpoint of associative memory, such a procedure should provide considerable difficulties at the time of retrieval, since the experimenter has little or no control over the associations the subject may have formed during list learning and the experimenter provides no specific cues at the time of retrieval. All of the specific retrieval cues must be supplied by the subject, and free recall performance should and does depend substantially on the subject's ability to generate such retrieval cues. To achieve good scores on free recall tests, Jenkins and Russell, Bousfield, Deese, Tulving, and others showed that subjects tend to cluster items that are highly associated to each other or form the items into common category labels such as "birds," "animals," "cities," and the like.

Category cues supplied by the experimenter in acquisition or retrieval are particularly helpful.[14]

It is not at all obvious why these effects should occur, if memory for the items consisted of storage in successive locations on a tape. Free recall of at least the last list presented should just consist of playing back the last section of tape. Category cues and associations between items ought to be irrelevant. For lists learned a longer time ago, there might be some uncertainty concerning where the list began and ended on the tape, but once the first and last items were identified, recall of everything in between should be unaffected by category cues and associations. This particular experiment has never been performed, but it is certain that the effects of category cues and inter-item associations on free recall would still be present even when the boundary items of the list were explicitly presented at the time of recall.

Spacing Judgments

Hintzman and Block presented subjects with a list of 19 words presented on a screen at a rate of five seconds per word. Some words appeared twice in the list, others only once. After presentation of the list, the test consisted of pairs of words which might be two repetitions of the same word (*A . . . A*) or two different words (*A . . . B*). Subjects were to estimate the number of words that had intervened either between the two repetitions of the same word or between the two different words. As shown in Figure 9-1, subjects showed some ability to judge the prior spacing between repeitions of the same item (*A . . . A*), but no ability to judge the prior spacing between different items (*A . . . B*).[15] If the memory of a list of words consisted of a sequence of pattern representatives for the words stored in successive locations, as in a tape recording, spacing judgments for two different words ought to be equivalent to spacing judgments for two occurrences of the same word. The significant difference in spacing judgments under these conditions, therefore, contradicts the nonassociative tape recording theory of memory.

An associative theory holds that the second time *A* is presented, it acti-

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[14] J. J. Jenkins and W. A. Russell, "Associative Clustering During Recall." *Journal of Abnormal and Social Psychology*, 1952 (47), 818-21. W. A. Bousfield, "The Occurrence of Clustering in the Recall of Randomly Arranged Associates." *Journal of Genetic Psychology*, 1953 (49), 229-40. J. Deese, "Influence of Inter-Item Associative Strength upon Immediate Free Recall." *Psychological Reports*, 1959 (5), 305-12. E. Tulving, "Subjective Organization in Free Recall of 'Unrelated Words'." *Psychological Review*, 1962 (69), 344-54. E. Tulving, "Intratrial and Intertrial Retention: Notes Toward a Theory of Free Recall Verbal Learning." *Psychological Review*, 1964 (71), 219-37. E. Tulving and J. Psotka, "Retroactive Inhibition in Free Recall: Inaccessibility of Information Available in the Memory Store." *Journal of Experimental Psychology*, 1971 (87), 1-8. E. Tulving, "Cue-Dependent Forgetting." *American Scientist*, 1974 (62), 74-82.

[15] D. L. Hintzman and R. A. Block, "Memory for the Spacing of Repetitions." *Journal of Experimental Psychology*, 1973 (99), 70-74.

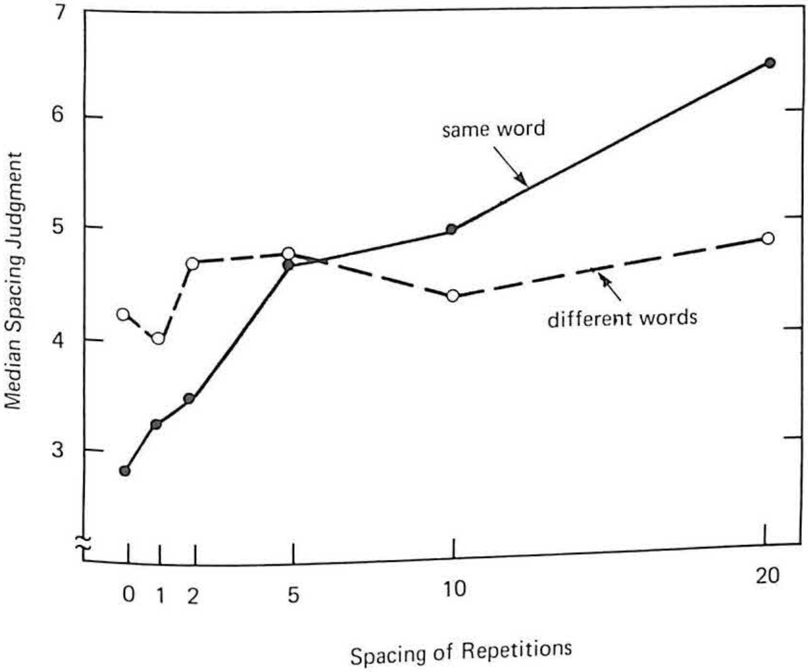

Figure 9-1. Median judgments of spacing for same word (*A . . . A*) and different word (*A . . . B*) test pairs (from Hintzman and Block. Copyright 1973 by the American Psychological Association. Reprinted by Permission.)

vates the same *A* representative as before, which should result in recognition memory for the repetition and sometimes in a recency judgment for how long it had been since *A* was previously presented. For example, the second time *A* is presented the subject may think to himself, "There's *A* again. I saw it before about ten items back." In such cases there will be acquisition of a new associative trace that encodes the spacing information for *A . . . A*, but there will be no such trace for *A . . . B*.

CHUNKING

Chunking plays an important role in long-term verbal learning, as it does in so many other learning and memory phenomena. Indeed the support for chunking is so widespread that the principle has already penetrated to the broader culture in the form of a rather well-known joke. In the final examination of a psychology of learning course, one student is sitting with his head in his hands, apparently deep in thought. The professor, observing that the student has not written a word for 20 minutes, walks over and asks what is wrong. The student answers, "Well, I did just what you said to do, I chunked the material. First, I read over the text and my lecture notes and condensed all the ideas into a ten-page outline. Then I reduced this to three file cards, then to three sentences, and finally to a single word. But now I can't remember the word." "Bullshit," said the professor. "That's it!", said the student.

Underwood and Schultz did a series of studies to explore the notion that when a subject learns a serial or paired-associate list, there are at least two different phases of the list-learning process: learning the responses and learning the associations between stimuli and responses. If the response elements are nonsense syllables or other nonunitary, poorly integrated, verbal material, subjects first learn to associate the parts of the responses to form single units. In terms of the current theory, they form chunk nodes. After they form chunk nodes for the responses, they can then more easily associate the stimulus nodes to the response nodes. If the stimuli are poorly integrated verbal units, subjects may sometimes chunk stimulus elements as well, though this is not so essential to correct performance in most of these tasks.[16]

Material that has been chunked together to form a familiar single unit appears for most purposes to function as a single unit in learning and memory. For example, Glanzer and Razel found that free recall of words containing two syllables (donkey, chestnut, earthquake) was at least as good as recall of monosyllabic words (elm, yawn, scrap). At a somewhat higher level Bower demonstrated that familiar three-word phrases (ballpoint pen, birth control pill, turtleneck sweater, good old days) can function as single units in lists of items to be recalled, but that unfamiliar three-noun compounds (couch, flag, sun) function as if they were three separate units. The familiar three-word phrases were recalled in a perfect all-or-none manner—that is, there were no partial recalls—but partial recall of the three-noun compounds was common. Furthermore, the familiar three-word phrases were recalled virtually as often as single words.[17]

It is now clear that the process of associating two words in a paired-associate learning experiment is not a matter of forming a horizontal association from one to the other. Paivio, Bower, and many others have demonstrated that learning paired associates is greatly facilitated by generating a unitary visual image that contains the concepts represented by the two words and relates them in some way. For example, Bower studied paired-associate learning for 100 pairs of unrelated concrete nouns such as dog-bicycle. Subjects were given five seconds to learn each pair, and a cued recall test was given after every 20 pairs for the preceding 20 pairs. (In cued recall, the stimulus is presented and the subject attempts to recall the response.) After all 100 pairs had been presented and tested once each, a final cued recall test was administered. One group of subjects was instructed to associate the nouns by imaging a visual scene in which the two objects were interacting in some way (a dog riding a bicycle, a dog jumping over a bicycle, etc.). The other group received typical, neutral, paired-associate learning instructions to "learn the pairs so the stimulus (left member) could cue recall of the response (right member)." On the final recall test the imagery group recalled about 80 percent of the responses to stimuli, while the control group recalled about 50 percent.[18] This enormous difference is typical of the effectiveness of learning by interactive imagery.

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[16] B. J. Underwood and R. W. Schulz, *Meaningfulness and Verbal Learning.* Chicago: Lippincott, 1960.

[17] M. Glanzer and M. Razel, "The Size of the Unit in Short-Term Storage." *Journal of Verbal Learning and Verbal Behavior,* 1974 (13), 114-31. G. H. Bower, "Chunks as Interference Units in Free Recall." *Journal of Verbal Learning and Verbal Behavior,* 1969 (8), 610-13.

Rohwer and others, following the lead of Epstein, Rock, and Zuckerman, demonstrated that memory for paired associates can be greatly facilitated by embedding the two words into a meaningful proposition (sentence) that unites them into some common idea. For example, a pair such as boy-turtle might be learned by embedding the pair into a sentence such as "The *boy* looked for his lost *turtle*." As Asch, Ceraso, and Heimer and Epstein, Rock, and Zuckerman demonstrated, associations between pairs of visual forms are also greatly facilitated by learning them as parts of a unitary visual image.[19] (An example of this is shown in Figure 9-2). The beneficial effects of chunking obtained even though the recall test involved decomposing the picture into parts, which is more similar to the condition in which the pairs are learned as separate parts. The effects of unitization (chunking) are so strong that they overcome any such negative factor.

The beneficial effects of semantic chunking also apply to material more complex than pairs of words. Kintsch, Crothers, and Jorgensen studied short-term memory for word triples using a distractor paradigm over re-

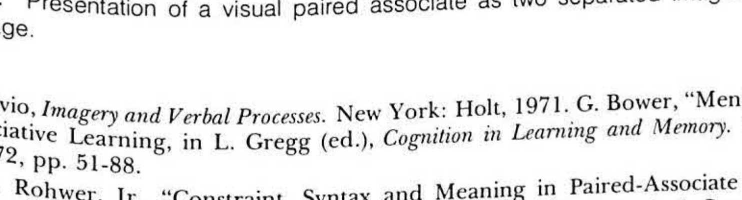

Figure 9-2. Presentation of a visual paired associate as two separated images and as a unitary image.

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[18] A. Paivio, *Imagery and Verbal Processes.* New York: Holt, 1971. G. Bower, "Mental Imagery and Associative Learning, in L. Gregg (ed.), *Cognition in Learning and Memory.* New York: Wiley, 1972, pp. 51-88.

[19] W. D. Rohwer, Jr., "Constraint, Syntax and Meaning in Paired-Associate Learning." *Journal of Verbal Learning and Verbal Behavior,* 1966 (5), 541-47. S. E. Asch, J. Ceraso, and W. Heimer, "Perceptual Conditions of Association." *Psychological Monographs: General and Applied,* 1960 (74), Whole No. 490, 1-48. W. Epstein, I. Rock, and C. B. Zuckerman, "Meaning and Familiarity in Associative Learning." *Psychological Monographs,* 1960 (74), Whole No. 490, 1-22.

tention intervals ranging from 3 to 24 seconds. Subjects were prevented from rehearsing during the retention interval by the requirement to start from a three-digit number and count backwards by threes as fast as possible until the experimenter gave a signal indicating that they were to recall the three words. They found that memory performance could be greatly improved via instructions to form a phrase or sentence that in some way connected the three words into a single unit. A variety of control conditions demonstrated that the learning superiority under these conditions occurred because the subjects formed a single chunk that integrated all three words into a single unit rather than because the instructions induced a higher semantic level of processing of the three words. For example, in one control condition subjects were instructed to form an appropriate separate phrase or sentence for each word (the phrase *the ferocious dog* or the sentence *the dog barks* for the word *dog*). Even when subjects were allowed more time for this type of separate semantic processing and elaboration, memory for the three words was substantially inferior to the condition in which the three words were integrated into a single chunk.[20]

Horowitz and others have studied *redintegrative memory,* the kind of memory in which a subject is presented with a picture, story, sentence, or phrase composed of several parts and is later given some of the parts and asked to remember the rest, or to reinstate the whole from some of the parts.[21] It now appears that a great deal of human conceptual memory is redintegrative. Most conceptual memory probably involves the formation of propositions and images that unite several constituents into a single higher-level chunk. The psychologists who emphasized the importance of structure and organization in human memory were clearly correct, though it should also be clear that there is no conflict between a vertical network organization and the assumption of associative memory.

It is instructive to consider one of the likely reasons our associative memories should have the chunking property of defining new nodes to stand for a set of old nodes. We could have a chunk be represented by the set of nodes representing its constituents. The association of two chunks could proceed by associating every node in one set to every node in the other set. However, since the same constituent nodes would appear in many different chunks, there would quickly be a large number of interfering associations. Defining a new node to stand for a particular combination of old nodes greatly reduces the susceptibility to associative interference.

One final point needs to be made concerning the relation between vertical and horizontal associations. The chunking capacity of defining a new

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[20] W. Kintsch, E. J. Crothers, and C. C. Jorgensen, "On the Role of Semantic Processing in Short-Term Retention." *Journal of Experimental Psychology,* 1971 (90), 96-101.

[21] L. M. Horowitz and L. S. Prytulak, "Redintegrative Memory." *Psychological Review,* 1969 (76), 519-31.

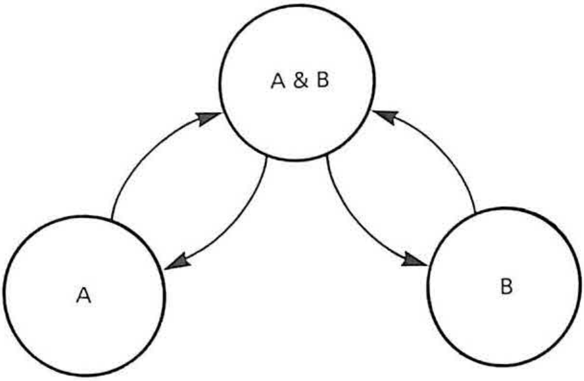

Figure 9-3. Upward and downward associations from the constituent nodes *A* and *B* to the chunk node *A* + *B*. A "forward" association from *A* to *B* is mediated by a chain of two associations: upward from the *A* node to the *A* + *B* chunk node and downward from the *A* + *B* chunk node to *B*. A "backward" association from *B* to *A* uses a chain composed of the other two associations.

node to represent a combination of old nodes by means of vertical associations is an addition to the capacities of a purely horizontal associative memory, with all its capacities and more. Any chunk node for *A* + *B* must have upward associations from the individual *A* and *B* nodes to the chunk node and also downward associations from the chunk node to its *A* and *B* constituents (see Figure 9-3). Thus, a chain of two links, upward from *A* to *A* + *B* and downward from *A* + *B* to *B*, can be the equivalent in a vertical associative memory of a single direct link from *A* to *B* in a horizontal associative memory. For many purposes, therefore, it is still reasonable to discuss forward associations from *A* to *B* and backward associations from *B* to *A* without concern for mediation by an intermediary chunk node. A discussion of these matters is contained in the following section.

TYPES OF ASSOCIATIONS

Forward and Backward Associations

In learning a paired-associate list (*AB*, *CD*, *EF* . . .) the subject must form associations from *A* to *B*, *C* to *D*, *E* to *F* and so forth. These are called direct forward associations, because they go forward in time (and from the given information to the goal information). In many paired-associate learning tasks, all a subject needs to learn are the forward associations; but in strengthening the forward associations, it appears that a subject also simultaneously strengthens backward associations, from the response node to the stimulus node. To some extent the same is true in serial learning, where subjects that have learned a list in forward order have some ability to repeat the list backwards.

Under many conditions the ability to perform backward recall in serial or paired-associate memory is inferior to the ability to recall in the forward direction, which is the basis for the assumption that backward associations are weaker than forward associations. Asch and Ebenholtz challenged this assumption with the principle of associative symmetry, which asserts that associations are bidirectional rather than unidirectional, and that forward and backward associations are equal in strength. According to Asch and Ebenholtz, the reason backward recall was typically inferior to forward recall in paired-associate learning was the frequent choice by experimenters of stimulus items less well integrated than the response items, and that even when the materials used for stimulus and response items are equivalent subjects tend to chunk response items more than stimulus items, which makes the response items more accessible in recall than the stimulus items. When this accessibility is controlled, Asch and Ebenholtz claimed that associative symmetry would be obtained.[22]

Although stimulus and response items must obviously be equivalent types of items, many of the other procedures advocated by Asch and Ebenholtz to insure equal accessibility of stimuli and responses resulted in considerable weakening of the temporal asymmetry between the two items. This is the very basis for the distinction between forward and backward associations. For example, simultaneous visual presentation of pairs and recall of both elements of the pair using a "free recall" procedure tends to permit a subject to learn and recall pairs in either temporal order. With simultaneously presented, word-word pairs, Murdock and others have often obtained associative symmetry.[23] This means that *spatial* position is irrelevant. However, obtaining associative symmetry with such a procedure has little meaning for the original *temporal* distinction between forward and backward associations.

Wollen and his colleagues have performed the most extensive and definitive investigations of associative symmetry in paired-associate learning. Of course they use equivalent *S* and *R* items. They also use a very well-controlled procedure of alternating study trials (in which subjects must pronounce the stimulus and response members in strict temporal order) with response trials (in which the subject is tested in either the forward—*S-R*—or backward—*R-S*—direction). This equates for response availability and intent to learn in one direction or the other and leaves temporal order of activating the *S* and *R* nodes on study trials as the only manipulated variable. This well-controlled procedure yielded clear evidence that forward associations are stronger than backward associations, though the strength of backward associations is also substantial.[24]

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[22] S. E. Asch and S. M. Ebenholtz, "The Principle of Associative Symmetry." *American Philosophical Society*, 1962 (106), 135-63.

[23] B. B. Murdock, *Human Memory: Theory and Data.* Potomac, Md.: Lawrence Erlbaum Associates, 1974, pp. 126-29.

Paired-associate learning is generally a better controlled procedure for answering theoretical questions because the stimuli and responses are separate items and can be independently manipulated. In this case, however, the earliest definitive piece of evidence obtained regarding associative symmetry was that backward recall in serial list learning is invariably slower and/or less accurate than forward recall. This inferiority of backward recall is true for both well-learned serial lists (try to recite the alphabet backwards) and for immediate memory (look up a telephone number and recall it in the backward direction). Since every item in a serial list is both a stimulus item and a response item, there can be no difference in the accessibility of the items in either direction. Hence, although it appears to be clearly true that backward associations are strengthened simultaneously with forward associations, forward associations are probably stronger, when strict control is exercised on the temporal order of activation of nodes representing items.

To date there has been little interest in whether forward and backward associations are qualitatively different. Obviously, we can distinguish the forward and backward direction, because subjects are able to comply with instructions to recall in either direction in a serial list. Subjects starting in the middle of a list typically do not give the stronger forward associate to an item when they are instructed to recall in the backward direction. This is just one example of the fact that we have many different types of associations to any given item. Perhaps there are different labels on the links that connect the nodes of associative memory, or perhaps a more complex structure of associations is formed.

Remote Associations

In serial list learning the association between adjacent items, whether forward and backward, is considered a direct association. Associations between nonadjacent items (*AC, CA, BF, FB* . . .) are known as remote associations. Ebbinghaus defined the concept and devised the method of derived lists to demonstrate their existence and measure the decrease in strength with increasing remoteness.[25]

There is no denying that subjects are able to recall remote items in either the forward or backward direction from a probe item, but to demonstrate the existence of remote associations, it is necessary to insure that there is no mediation via a chain of direct associations or via serial position concepts. Ebbinghaus's method of derived lists probably avoided mediation by chains of direct associations, but it has other problems that render any interpretation in support of the existence of remote associations completely inconclusive at present. If the successive members of a serial list are labeled 1, 2, 3, 4, 5, 6, 7, 8, 9, a first-order forward derived list would have the form 1, 3, 5, 7, 9, 2, 4, 6, 8, a second-order derived list has the form 1, 4, 7, 2, 5, 8, 3, 6, 9, etc. That is to say, the items in the list are rearranged to form a derived list in which formerly remote associations are now adjacent. Ebbinghaus reasoned that if positive transfer were obtained from learning the first list to learning a second (derived) list, then this would be evidence for the existence of remote associations.

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[24] K. A. Wollen, R. A. Fox, and D. H. Lowry, "Variations in Asymmetry as a Function of Degree of Forward Learning." *Journal of Experimental Psychology*, 1970 (86), 416-19.

[25] Ebbinghaus, *Memory*.

First it should be noted that this procedure does not adequately control for positive transfer based on serial position-to-item associations, which are now known to be very important in the learning of serial lists. Since the first item in the original list is also the first item in the derived list, there might be positive transfer based on this fact alone. Factors such as these would be better controlled by using *circular lists* that have no unique beginning point. However, even with circular lists there is no way of preventing a subject from imposing a serial ordering on the elements of the list, and subjects very frequently do this.

Many subsequent investigators have not found the positive transfer that Ebbinghaus found for derived lists.[26] This may be because Ebbinghaus used an extremely rapid rate of presentation (approximately 0.4 seconds per item) in learning his lists, and subsequent investigators have always employed much slower rates. Ebbinghaus's rapid rate of presentation may have simultaneously prevented indirect mediation by chains of direct item-to-item associations and mediation by serial position concepts, simply because there was insufficient time. Also Ebbinghaus used himself as the subject and carefully avoided complex encoding strategies. In addition, a rapid rate of presentation may facilitate the formation of remote associations, since the more rapid the rate of presentation, the greater the degree of temporal contiguity for a given remote association.

At present the existence of remote associations is neither proved nor disproved. However even if they do exist, remote associations by any meas-

[26] N. J. Slamecka, "An Inquiry into the Doctrine of Remote Associations." *Psychological Review*, 1964 (71), 61-76. B. R. Bugelski, "In Defense of Remote Associations." *Psychological Review*, 1965 (72), 169-74. K. M. Dallett, "In Defense of Remote Associations." *Psychological Review*, 1965 (72), 164-68. N. J. Slamecka, "In Defense of a New Approach to Old Phenomena." *Psychological Review*, 1965 (72), 242-46. D. T. Hakes and R. K. Young, "On Remote Associations and the Interpretation of Derived-List Experiments." *Psychological Review*, 1966 (73), 248-51. W. Shebilske and S. M. Ebenholtz, "Ebbinghaus' Derived-List Experiments Reconsidered." *Psychological Review*, 1971 (78), 553-55.

ure, are substantially weaker than direct associations, which raises the question of their functional significance outside of rapid serial list learning. They may have little or no significance. Alternatively, the capacity for forming remote associations may be integrally related to the chunking capacity of the human mind—that is, the capacity to form remote associations may be identical to the capacity to chunk a number of successively presented events into a single node. Viewed in this light, increasing remote associative capability might be integrally related to intelligence. It is an interesting speculation, but that is all.

Implies and Coimplies

Consideration of the vertical associations formed via the chunking process produces yet another potential distinction between different types of associations, the distinction between up and down in a hierarchy. If two elements *A* and *B* are associated to a higher-level chunk node, then the associations from *A* to the chunk node and from *B* to the chunk node are *upward* associations, while the associations from the chunk node to *A* and to *B* are *downward* associations, as illustrated in Figure 9-3. Translating these spatial notions into logical terminology, the relationship between a chunk node and its constituents (*A* and *B*) has the character of a logical *implies* relation, which means that the chunk node implies all of its constituents, since a chunk is a conjunction of its constituents. There is no familiar and appropriate logical term, for the logical relation in the upward direction, from the constituents to the chunk, so I have invented the term *coimplies*, since each of the constituents along with the other constituents coimplies the chunk.

In the next chapter we shall see how the semantic memory representation of an entire proposition (sentence) can be considered a chunk whose constituents are the phrases, and ultimately the concepts that compose the proposition. Retrieval from such a semantic memory appears to require some way to distinguish between associations that travel upward in the hierarchy and those that travel downward. We generally do not want merely to pick the strongest association to a node. Semantic memory models such as those of Anderson and Bower or Norman and Rumelhart explicitly distinguish between these two directions of associations in a semantic hierarchy or network, but the support for this distinction is not so much experimental evidence as it is the absence of any theoretical alternative.[27]

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[27] Anderson and Bower, *Human Associative Memory*. D. E. Rumelhart, P. H. Lindsay, and D. A Norman, "A Process Model for Long-Term Memory," in Tulving and Donaldson, *Organization of Memory*. D. A. Norman, D. E. Rumelhart, and the LNR research group, *Explorations in Cognition*. San Francisco: Freeman, 1975.

SUMMARY

1. One can distinguish many types of memory such as: (1) item, order, and associative memory; (2) recency, frequency, spacing, duration, and modality memory; (3) reproductive versus reconstructive memory, and (4) semantic versus episodic memory. There is little reason to suppose that these logical differences correspond to any significant psychological differences in memory storage. Perhaps the strongest case can be made for distinguishing certain recency judgments from other forms of memory.
2. The enormous capacity of rapidly accessible human conceptual memory indicates direct access to memory traces with little or no search in most cases.
3. Judgments of the recency and ordering of events fall far short of what a nonassociative (tape recorder) memory could accomplish.
4. Associations between serial position concepts and items play a major role in serial learning, although item-to-item associations also make some contribution. What is learned depends on what the mind thinks about, which is not always under perfect experimental control.
5. Proactive interference is the negative effect of prior learning on acquisition, storage, or retrieval of subsequently learned material.
6. Retroactive interference is the negative effect of subsequent learning on the storage or retrieval of previously learned material.
7. The magnitude of proactive and retroactive interference increases sharply with increases in the similarity between the interfering material and the material to be remembered.
8. In learning a serial list by the part method, there is considerable difficulty learning to connect the parts. This is expected with an associative memory, since the ratio of associations strengthened per event rehearsed is especially unfavorable.
9. Free recall of long lists of words demonstrates substantial organization or clustering by groups of words that are associated to each other or to a common superordinate (category) concept, rather than organization by temporal contiguity. This result is also contrary to what would be expected with a nonassociative (tape recorder) memory.
10. Ability later to judge the temporal spacing between two occurrences of the same word (*A* . . . *A*) is substantially superior to the ability to judge the spacing between occurrences of two different words (*A* . . . *B*). This difference appears to be inexplicable with a nonassociative memory.
11. Human associative memory appears to have the capacity to form vertical associations to specify a new chunk node to represent a combina-

tion of elements. The chunking process may play an important role in concept learning, the response-integration phase of paired-associate learning, and the learning of associations between elements by incorporation into a higher-order propositional or image unit.

12. When concept nodes are activated in close temporal succession, both the forward and the backward associations are strengthened, but the forward association is stronger than the backward. There is no unambiguous evidence for remote associations, but they are a possibility. A vertical association downward from a chunk to one of its constituents is a logical *implies* relation. An association in the upward direction from a constituent to the chunk is logically a *coimplies* relation. These may or may not be psychologically distinct types of associations.

10 Semantic Memory

OBJECTIVES

1. To point out that we remember primarily the meaning of the sentences we hear and not the exact words and phrases.
2. To discuss concepts, the most basic units of coding in semantic memory. Concepts can be activated by a large variety of cues, both (1) from their referents (the things they stand for) if they are concrete concepts, and (2) from words and phrases that are the verbal signals for concepts.
3. To discuss the coding of higher-level units in semantic memory: (1) conceptual compounds (predicates, contexts), which are cued by phrases, and (2) propositions (containing at least a subject and a predicate), which are cued by phrases, clauses, and sentences.
4. To present a clear conception of the role of recognition of familiar material in answering questions (retrieval) and in storing new knowledge in semantic memory (acquisition).
5. To discuss human capacities for inferring the truth or falsity of new propositions based on one or more propositions stored in semantic memory and to provide examples of six types of inferences.
6. To discuss the two aspects of the meaning of concepts: (1) referential meaning (its lower-level attribute constituents) and (2) relational meaning (its relations to other concepts by means of the propositions of which it is a part).
7. To discuss the concept-learning process, including observation and inference (the two basic methods of concept learning) and the role of attention and negation.
8. To explain the notion of a prototype, which is a basic set of attributes possessed by an ideal (central) example of elementary concrete concepts.
9. To explain Rosch's hypothesis of basic concepts, which are the most inclusive concepts characterized by a single prototype.

10. To discuss the role of experience in children's acquisition of syntax (grammar).

Although structural verbal memory is vitally important for understanding verbal input and communicating with others, the basic purpose of the verbal modality is not to encode words and their structural—phonetic and graphic—constituents, but rather to encode meanings. Structural verbal memory is a means to the end of improving our semantic memories by permitting the semantic memory of one person to communicate with the semantic memory of another. Most of our phonetic and graphic verbal learning is complete by the time we reach adulthood. Virtually all the long-term verbal learning of older children and adults consists of modifications of higher-level semantic memory.

There are times when even adult human beings learn new words or memorize a poem or prose passage, but these are the exceptions. Mostly they encode the meanings of the verbal material they hear and read, not the exact words and phrases used to convey those meanings. Sachs demonstrated this experimentally within the context of a recognition memory paradigm. She presented subjects with prose passages to read, then subjects were immediately required to judge whether a test sentence was structurally identical—that is, identical in every respect including meaning, syntax, and words—to some sentence presented previously in the passage. In some cases the test sentence was identical. In other cases it was identical in meaning but different in syntax or wording, such as conversion from active to passive voice or changes in words or word order that did not alter the meaning. There were also test sentences that were altered semantically (interchanging subject and object, negation, substitution of a word that occurred elsewhere in the passage) so as to change the meaning. The semantic changes were constructed so as to prevent identification of changes owing to the introduction of words that had not occurred in passage.

There were three retention intervals (the time between the test sentences and the relevant prior sentence): zero (when the relevant prior sentence occurred at the end of the prior passage), 27 seconds of intervening prose material (earlier in the passage), and 46 seconds of intervening material. When the test sentence was presented immediately following the relevant prior sentence, recognition of both semantic and structural changes was extremely good. At the longer retention intervals, recognition of changes in meaning was still extremely high, but recognition of purely structural changes dropped to nearly chance levels.[1]

Sachs' study indicates that structural information concerning the form of a sentence often is stored for a very short time—just enough for comprehension. Long-term storage of sentences is for their meaning, independent of original form. Subsequent studies have indicated that there are conditions under which people are able to remember the purely structural properties of sentences for longer than a few seconds, but under most circumstances long-term memory for sentences is concerned almost exclusively with memory for meaning.

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[1] J. S. Sachs, "Recognition Memory for Syntactic and Semantic Aspects of Connected Discourse." *Perception and Psychophysics,* 1967 (2), 437-44.

WORD AND CONCEPT NODES

The two most likely basic nodes for representation in semantic memory are words or concepts. For the moment let's ignore the distinction between words and concepts and consider evidence for the existence of verbal nodes larger than phonemes, letters, or sensory attributes (features). For the present discussion these larger nodes will be called words, concepts, semantic nodes, or word-like nodes, more or less interchangeably.

The Evidence for Semantic Nodes

There are many ways to make us think of some word or concept. The name can be presented visually or auditorally, and we can also see, hear, or touch the referent itself. For example, one can hear or see the word *cat* or one can see a cat, hear it meow, or touch it. Furthermore, there are many different visual or auditory stimuli that evoke the cat concept, such as different breeds of cats, different views of the same cat, hissing, meowing, purring, etc. All these sets of stimuli that evoke the cat concept do not have a common set of attributes at the sensory attribute (structural feature) level. It would be very clumsy to learn facts about cats by establishing associations with all the separate sets of structural attribute representatives that signal the cat concept. Since it appears that knowledge obtained about cats is activated by one set of cues and transfers completely to the same concept activated by a different set of cues, some single node standing for the word or concept *cat* would seem to be indicated.

Second, it is well established that words are more easily recognized when they are presented in a grammatical sentence than when they are spoken in isolation.[2] Such contextual effects on recognition are easily derived from a theory in which the context induces a bias (attentional set) for certain concept or word nodes. Such biasing effects could be achieved by priming

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[2] G. A. Miller, G. A. Heise, and W. Lichten, "The Intelligibility of Speech as a Function of the Context of the Test Materials." *Journal of Experimental Psychology*, 1951 (41), 329-35. H. Rubenstein and I. Pollack, "Word Predictability and Intelligibility." *Journal of Verbal Learning and Verbal Behavior*, 1963 (2), 147-58. A. N. Stowe, W. P. Harris, and D. B. Hampton, "Signal and Context Components of Word-Recognition Behavior." *Journal of the Acoustical Society of America*, 1963 (35), 639-44.

(biasing) all the possible featural or segmental constituents (components) of all the likely words, but it is obviously much easier to achieve such biasing by priming word (or concept) nodes, rather than by priming all the nodes for structural constituents of words.

Third, words that occur more frequently in a language are easier to recognize than words that occur less frequently.[3] This *word-frequency effect* seems easily explained by means of a bias (set) to perceive or respond to more familiar words than to less familiar words. It seems unlikely that the effect could be attributed to systematic differences at the segmental (letter or phoneme) or featural (attribute) levels between frequently and infrequently occurring words.

Finally, one of the most impressive supports for the existence of word-like nodes is Reicher's *word-superiority effect* in tachistoscopic visual recognition. Reicher and others demonstrated that under certain conditions the perception of letters in words is superior to the perception of letters in comparably long nonwords and sometimes even better than the perception of an isolated single letter. For discrimination of letters in words, subjects were asked to choose which of two words differing in only a single letter (for example, *bats* and *rats*) was presented on a given trial. For discrimination of letters in comparably pronounceable nonwords the alternatives might be *bast* and *rast*. Naturally the single-letter discrimination would be between *b* and *r*. The result (which has been obtained reliably under some conditions but not others) is that the *b* versus *r* discrimination is better when the letters are embedded in words than when they are embedded in pronounceable nonwords and better even than when a single letter is presented in isolation.[4] The word-superiority effect provides a very convincing demonstration of the existence of word nodes that can aid in the discrimination of letter constituents. Furthermore, the fact that words are superior to comparably pronounceable nonwords indicates that the result is due to word nodes, rather than merely to syllable nodes.

Words and Concepts

It is important to distinguish *words*, which are high-level structural nodes, from *concepts*, which are basic-level semantic nodes. Many single words have a multiplicity of meanings. Some meanings of the same word are closely related, but others are less closely related or even unrelated. Even a single dictionary definition of a word can refer to different concepts in different contexts. In one context *bear* may refer to bears in general, in another context to a particular species of bear or to a particular bear. It might even refer to a child's teddy bear, or to a fictitious cartoon character that can talk and think like a human being. All of these concepts are different and must be distinguished in semantic memory, if we are to avoid hopeless confusion.

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[3] D. Howes, "On the Relation Between the Intelligibility and Frequency of Occurrence of English Words." *Journal of the Acoustical Society of America*, 1957 (29), 296-305. M. R. Rosenzweig and L. Postman, "Intelligibility as a Function of Frequency of Usage." *Journal of Experimental Psychology*, 1957 (54), 412-22. I. Pollack, H. Rubenstein, and L. Decker, "Intelligibility of Known Message Sets." *Journal of the Acoustical Society of America*, 1959 (31), 273-79. C. Brown and H. Rubenstein, "Test of Response Bias Explanation of Word-Frequency Effect." *Science*, 1961 (133), 280-81.

[4] G. M. Reicher, "Perceptual Recognition as a Function of Meaningfulness of Stimulus Material." *Journal of Experimental Psychology*, 1969 (81), 275-80. D. D. Wheeler, "Processes in Word Recognition." *Cognitive Psychology*, 1970 (1), 59-85.

Not only does the same word refer to many different concepts in different contexts, often different words or phrases can be used to refer to the same concept. Synonyms and pronouns are the most obvious cases. Proper names versus definite descriptions of the same concepts, such as *George Washington* versus *the first president of the United States,* are another example. Definite descriptions are sometimes used in a way that makes distinct concepts from the entities they refer to, but under other conditions they are used as another way of referring to an entity that can be referred to by name. Thus on both logical and linguistic grounds it seem necessary to distinguish between concepts and words and probably to have separate nodes for each.

There is also experimental evidence for the existence of concept nodes. Perfetti and Goodman tested recognition memory for words that had previously been presented in sentence contexts that biased one meaning of a word with multiple meanings. For example, subjects in one group might have heard the word *top* in a sentence such as, "The man set up a ladder and climbed to the *top* of the house," while subjects in another group heard it used in a sentence that biased its meaning as a toy, such as "Jim's father bought him a *top* for a Christmas present, but Jim was too young to be able to spin it." After hearing a number of such sentences, subjects were given a list of words and asked to select those they recognized as having occurred in the preceding sentences. Some of the words in the recognition test had been presented in the preceding sentences (old words), some were new words that were semantically related to old words with the meaning that had been used in the prior sentence context (for example, *bottom* for *top* in one group, or *toy* for *top* in the other group), some were new words related to an old word with a meaning different from that used in the prior sentence, and some were control new words that were not specifically related to any old words. Compared to the frequency of falsely saying "yes" to control new words, Perfetti and Goodman found that the frequency of false recognition was increased for new words that were semantically related to the correct meanings of old words, but not for new words related to the other meanings of old words.[5]

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[5] C. A. Perfetti and D. Goodman, "Semantic Constraint on the Decoding of Ambiguous Words." *Journal of Experimental Psychology,* 1970 (86), 420-27.

Light and Carter-Sobell and Tulving and Thomson have demonstrated that recognition memory for a word is decreased by changing the verbal context in which it is first learned in a manner that changes its meaning. For example, if subjects are originally presented with the phrase *raspberry jam* and subsequently tested for recognition memory of *jam*, performance is much poorer when it is presented in the phrase *traffic jam* than when *raspberry jam* occurs in both learning and test. By contrast, little decrement in recognition memory for nouns occurs when the adjectives bias the same meaning of the noun, such as *raspberry jam* followed later by *strawberry jam.*[6]

MacKay has found that associations to ambiguous words (words with multiple meanings) take longer than associations to unambiguous words (words with one primary meaning or with closely related meanings). He controlled for a number of possibly confounding factors and concluded that so called "word associations" are actually between concept representatives rather than between word representatives.[7]

There is also evidence that subjects have word nodes as well as concept nodes, but it is less compelling. In the *raspberry jam* experiments, the subjects' ability to recognize the noun *jam* was still substantial, even when an entirely different meaning of the word was contextually biased. In addition, there appears to be a number of advantages to interpolating something like word nodes between phonetic or graphic nodes and concept nodes. Concept nodes must be activated by a large variety of different conjunctions of attributes. Word nodes appear to chunk the phonetic attributes characteristic of the name for a concept.

There is also evidence to support the existence of direct associations between phonetic and graphic nodes and concept nodes. For example, consider the *tip-of-the-tongue* phenomenon. Everyone has had the experience of not being able to recall a name. We know that the word is familiar, and that under other circumstances we have recalled it. We may feel that we are on the verge of recalling it and can even recall some of its attributes. A well-known experiment by Brown and McNeill created the tip-of-the-tongue state experimentally and demonstrated that subjects were able to recall beyond chance many of the segmental constituents (letters, phonemes, syllables) of words they could not recall. They could guess better than chance the number of syllables in the word, its initial letter, and words with similar sounds.[8] In the tip-of-the-tongue state, subjects know the concept that they are thinking of, since they can define it using other

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[6] L. L. Light and L. Carter-Sobell, "Effects of Changed Semantic Context on Recognition Memory." *Journal of Verbal Learning and Verbal Behavior,* 1970 (9), 1-11. E. Tulving and D. M. Thomson, "Retrieval Processes in Recognition Memory: Effects of Associative Context." *Journal of Experimental Psychology,* 1971 (87), 116-24.

[7] D. G. MacKay, Personal communication.

[8] R. Brown and D. McNeill, "The 'Tip-of-the-Tongue' Phenomenon." *Journal of Verbal Learning and Verbal Behavior,* 1966 (5), 325-37.

words. This ability to recall segmental constituents of a word but not the entire word suggests the existence of direct associations from concept nodes to segmental nodes.

Constituents

Several times in this text the term *constituent* has been used. Its meaning is similar to the meaning of *component*, and for many purposes it does no harm to think of *constituent* as meaning *component*. So why do we use the unfamiliar term? Skepticism of technical terms is definitely in order. Sometimes their meanings are no different from those of common terms, and sometimes their meaning is vaguer or otherwise less suitable for scientific communication than familiar terms. However, this is not always the case. Science depends vitally upon the invention of new precise concepts, and often it is important for clarity to give new technical concepts names that do not convey inaccurate meanings.

Such is the case with *constituent*. A component is a part of some whole and the whole is literally composed of its components. By contrast, a concept (chunk) is *cued* (activated) by various sets of its constituent attributes, but it is not *composed* of any one set of them or by all of them. The concept *represents* all of its constituents, much as your senator represents all of his or her constituents without being composed of them. If we lacked chunking capacity, and the representation of any set of attributes was only by activation of the set of attribute nodes, there would be no point in distinguishing the meaning of constituent and component. However, because sets of lower-level nodes come to be represented by a higher-level chunk (concept) node, it is more accurate to use the term constituent to refer to the lower-level nodes of a chunk (concept).

THE STRUCTURE OF SEMANTIC MEMORY

All the specific data and general principles that we have learned and remembered compose our semantic memory. In the present discussion it is assumed that semantic memory includes both our knowledge of specific data and general principles concerning the world and also our knowledge of the events that have occurred in our personal lives. *Semantic memory* is used here to refer to the highest level of verbal knowledge including all the propositions we have learned. *Episodic memory,* of the events of our personal lives, is assumed to be a part of semantic memory rather than a separate type of memory.

Associative Memory

Human verbal memory is associative. Most of the experiments that established the associative character of verbal memory have used pairs and serial lists of verbal items, but there is every reason to believe that this type of material is stored in precisely the same semantic memory that is used to encode all our propositional knowledge. For example, there is every reason to believe that most paired-associate learning occurs by means of embedding the pairs into meaningful propositions. Furthermore, studies of memory for sentences demonstrate the same associative interference phenomena characteristic of word-pair memory. As we discussed in Chapter 9, Anderson has shown that subjects are slower to recognize a proposition such as "The hippie is in the park" when either the person (hippie) or the location (park) is included in other propositions learned by the subject in the experiment.[9]

Phrase and Proposition Nodes

Although the structure of semantic memory is very much in question at the present time, the most attractive and parsimonious view is that the verbal associative structure characteristic of the lower levels of the verbal modality applies to higher levels of semantic memory as well. Anderson and Bower in their model of semantic memory assume that the structure of our semantic memory for a sentence such as "One summer at Cotton Lake Warren caught a walleye" would be as diagrammed in Figure 10-1.[10]

According to this theory, the highest-level constituents of a proposition are the *context* (which includes a *time* and a *location*) and a *fact* (which includes the subject, verb, and objects). The fact node (chunk or unit) follows a predicate grammar in that the constituents of a fact node are a *subject* and a *predicate*, and the constituents of the predicate node are a *verb* and *object(s)*. Thus, just as concepts such as *walleye* are themselves conjunctions

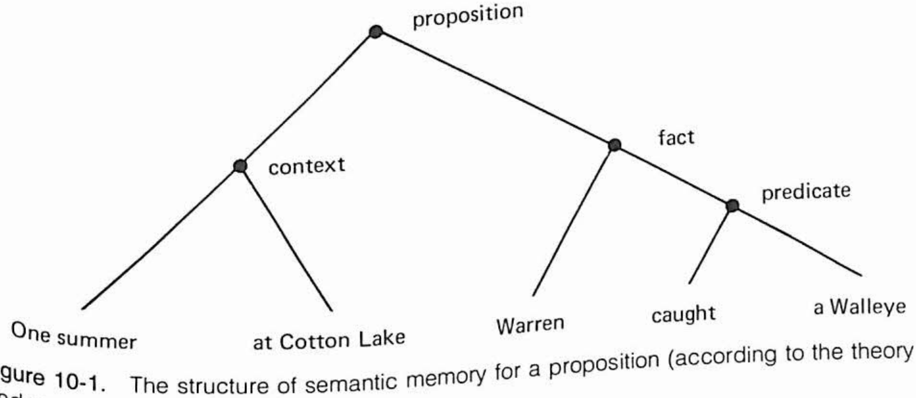

Figure 10-1. The structure of semantic memory for a proposition (according to the theory of Anderson and Bower).

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[9] J. R. Anderson, "Retrieval of Propositional Information from Long-Term Memory." *Cognitive Psychology*, 1974 (6), 451-74.

[10] Anderson and Bower, *Human Associative Memory*.

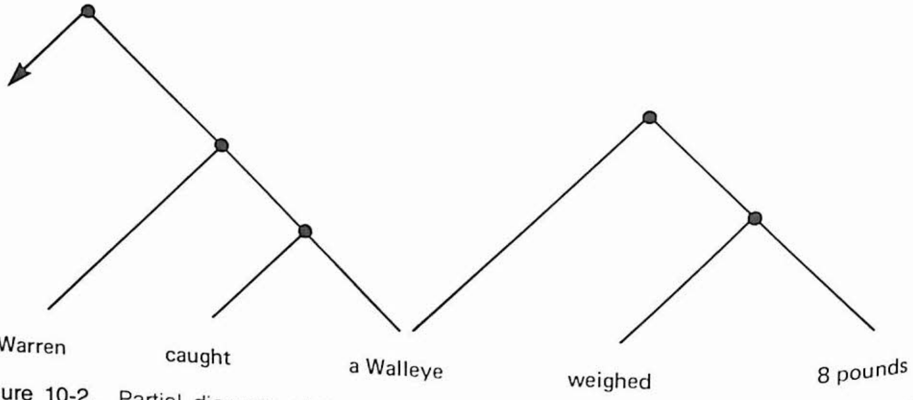

Figure 10-2. Partial diagram of the possible structure of semantic memory for a complex sentence that incorporates two propositions.

of lower-level attribute constituents, so a phrase node such as *caught walleye* is a conjunction of its lower-level concept constituents *caught* and *walleye*. Similarly, a fact node such as *Warren caught walleye* is a conjunction of the lower level nodes for *Warren* and *caught walleye*, etc. Thus, the relationship between propositions and concepts in semantic memory may be very similar to the relationship between concepts and attributes.

Many of the propositions we have stored in our semantic memories are more complex than the proposition shown in Figure 10-1. For example, consider "One summer at Cotton Lake Warren caught a walleye that weighed eight pounds." Such a sentence can be considered to be stored in semantic memory as two propositions that intersect at the concept *a walleye*, as diagrammed in Figure 10-2. Furthermore, human beings appear to be capable of learning complex embedded propositions such as "Glenn knows that one summer at Cotton Lake, Warren caught a walleye." The encoding of such a sentence in semantic memory might be as shown in Figure 10-3.

Our linguistic intuition provides some evidence for the assumptions regarding the structure of semantic memory illustrated in Figures 10-1, 10-2, and 10-3. Figure 10-3 accounts for the very consistent human jundgment that *Glenn* is more closely related to *knows* than to *caught* or to any other constituent of the embedded proposition, for example. The sentence structure shown in Figure 10-2 captures our intuition that the concepts *weighed* and *eight pounds* are more closely related to *walleye* than they are to any other constituents of the complex proposition, such as *Warren* or *caught*. Formal psycholinguistic experiments also support the assumption that complex sentences are represented in semantic memory by their component propositions. For example, in remembering sentences composed of two propositions, the ability to recall one of these propositions is greater when subjects are provided with a cue word from the same proposition than when they are provided with a cue word from the other proposition in

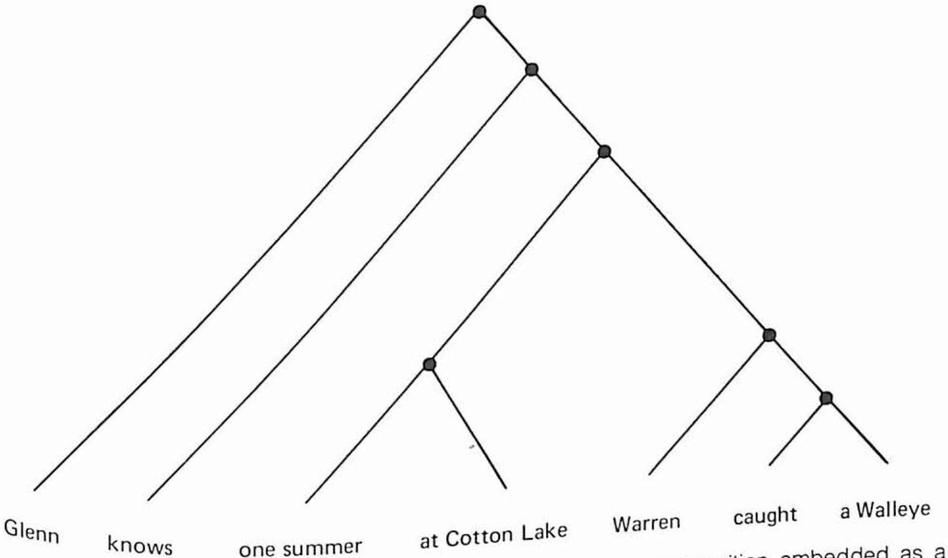

Figure 10-3. Possible structure of semantic memory for one proposition embedded as a constituent of another proposition.

the same sentence.[11] The hypothesis that the structure of semantic memory is based on the storage of propositional units is now rather well established.

In contrast to the wealth of evidence supporting the adequacy of a *between-propositional* analysis of sentences, there is little evidence to support any particular hypothesis of the *within-propositional* structure of semantic memory. Linguistic intuition provides a limited degree of guidance, by indicating for example that the object and the verb are more closely related to each other than the object and the subject are to each other. It has most often been assumed that propositions have a predicate syntax—that is, that the most basic constituents of a proposition are its subject and its predicate, the predicate being the verb and its objects. The Anderson-Bower theory deviates somewhat from the typical predicate grammer in its assumption that the contextual modifiers of a proposition are higher-order constituents rather than embedded constituents of the predicate.

Some support for a predicate syntax derives from the observation that the subject of a sentence is usually the better cue for the recall of the remainder of the sentence than the verb or the object.[12] Since the subject by itself is a constituent of the proposition (or fact) while the verb and the object are merely parts of the predicate constituent, this provides some evidence in support of a subject-predicate structure for the elementary propositions of semantic memory. However, matters in this area are still very unsettled.

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[11] *Ibid.*

[12] A. L. Blumenthal, "Prompted Recall of Sentences." *Journal of Verbal Learning and Verbal Behavior*, 1967 (6), 203-6. A. L. Blumenthal and R. Boakes, "Prompted Recall of Sentences." *Journal of Verbal Learning and Verbal Behavior*, 1967 (6), 674-76. L. M. Horowitz and L. S. Prytulak, "Redintegrative Memory." *Psychological Review*, 1969 (76), 519-31. S. J. Thios, "Memory for General and Specific Sentences." *Memory and Cognition*, 1975 (3), 75-77.

Semantic Integration

Semantic memory for compound or complex sentences appears to involve the formation of separate propositional node structures for each of the component sentences, with the structures intersecting at the concept or phrase nodes that the two propositions have in common.[13] One example of this was illustrated in Figure 10-2. Similarly, information presented in two separate sentences involving common concepts often results in a semantic memory structure that is indistinguishable from that created by presentation of the same information in a single compound or complex sentence. A very important experiment by Bransford and Franks showed that subjects frequently cannot remember whether several closely related pieces of information in a test sentence had previously been presented in the same sentence or in separate sentences. Bransford and Franks constructed sentences composed of anywhere from one to four related component propositions, such as: "The ants in the kitchen ate the sweet jelly that was on the table." This complex sentence has four component propositions: "The ants were in the kitchen," "The jelly was on the table," "The jelly was sweet," "The ants ate the jelly." First subjects listened to sentences that contained one, two, or three related component propositions and were told that their task was to listen to the sentences in order to answer questions about them later. They were thus given a set to recall the meaning and not the exact form of the sentences. Under this set, the results were analogous to those in the Sachs experiment: subjects remembered the component propositions but did not remember the exact sentences they had heard. Thus, when subjects were asked to state whether a test sentence was exactly identical to one they had heard, many falsely recognized sentences that included all four related propositions, even though they had never heard a sentence with all four component propositions during the acquisition period.[14] In this case at least, the same network structure of propositional components intersecting at common phrase and concept units appears to have been established regardless of how the component propositions were combined into sentences.

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[13] Anderson and Bower, *Human Associative Memory.*

[14] J. D. Bransford and J. J. Franks, "The Abstraction of Linguistic Ideas." *Cognitive Psychology,* 1971 (2), 331-50.

Context and Episode

The semantic memory theory of Anderson and Bower assumes that context nodes are associated to fact nodes via vertical associations to a common, contextually modified proposition node as illustrated in Figure 10-1. This provides an elegant explanation for our capacity to remember the events that have occurred in our life, what Tulving referred to as episodic memory. In the first place, all of the facts to be stored in our memory in a common context could be associated with the same context node. An episode or sequence of events could be represented by means of yet higher-order propositional nodes encoding what events followed what other events.

Alternatively, sequences of events or episodes may be encoded by horizontal associations between contextually modified proposition nodes, as illustrated in Figure 10-4. The word *then* is written on the horizontal association between two successive proposition nodes, but that does not necessarily mean the association is of a different form from other associations in semantic memory. When we tell a story based on memory of such an episode stored in our semantic memory, the transition from one event to another would be accompanied by some transitional word such as "then" to indicate temporal sequence, but that does not imply that the association is different in character from any other association. Not every word that we speak in a sentence needs to have a unique node or type of association representing it in semantic memory. The cue to use a certain word, particularly grammatical function words such as articles, prepositions, and conjunctions (including *then*), may be complexly determined by the network structure of nodes and associations being communicated.

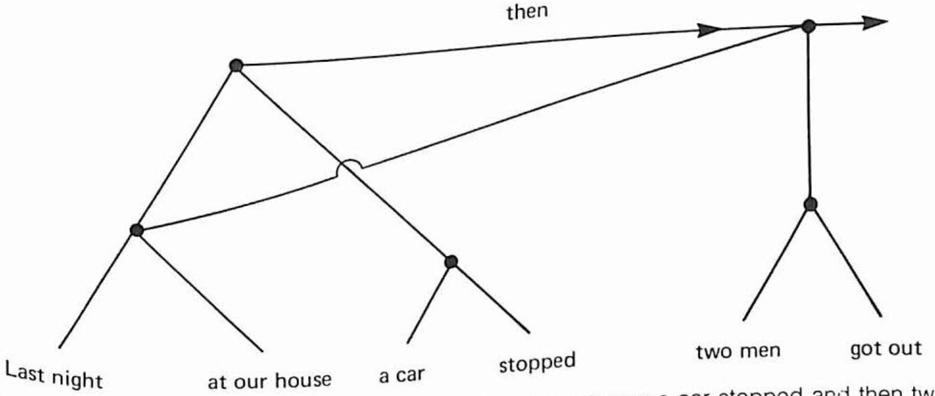

Figure 10-4. Encoding of the episode "Last night at our house a car stopped and then two men got out."

RECOGNITION AND ACQUISITION

Perceptual recognition is an important basic process in both the acquisition and the usage of semantic memory. In an associative semantic memory of the type human begins appear to possess, recognition involves associating an input sentence or some portion of that sentence with some subset of the existing node structure in semantic memory. When nodes already exist to represent an entire input sentence, we say that we have already learned the propositions expressed by that sentence—that such propositions are familiar to us. When only a portion of the input sentence can be mapped onto an existing node structure in semantic memory, then we say that that portion is familiar, but that the rest constitutes new knowledge. Recognition is an important process in the acquisition of new knowledge, since new knowledge should be associated to old knowledge to be maximally useful. When we are learning new material, we recognize as much of it as is familiar, and then we add on new associations and nodes to represent the remainder.

Recognition is an important part of acquisition, because human semantic memory is associative. If an input sentence were to be stored without reference to the identity of portions of that sentence to already existing knowledge, there would be tremendous duplication of memory storage. Furthermore, memory retrieval would be much more difficult, because related information would be stored at many different places in the memory system. The recognition process would then have to take place during retrieval, in order to unite information concerned with the same concepts but stored at different times.

RETRIEVAL

I use the term *retrieval* to refer to the elementary usage of semantic memory involved in answering yes-no questions ("Does Jane play bridge?") and *wh*-questions ("Who plays bridge?," "What did Steve do last night?," "Where is my bat?" etc.) Elementary questions like these can be answered by means of a single word or short phrase and thus have minimal problems with respect to the generation of grammatical (syntactic) speech. The wide use of objective testing illustrates the extraordinary degree to which one can test virtually any aspect of the contents of semantic memory by means of elementary yes-no and *wh*-questions.

Although there are some differences, yes-no questions correspond roughly to tests of recognition memory, while *wh*-questions are tests of recall. (A more precise analysis of recognition and recall will be given in

Chapter 15. For now we note that recognition is as critical a component of retrieval as it is of acquisition.) To answer a yes-no question, one determines whether all of the propositions in the input sentence are already represented by a node structure existing in semantic memory. If the propositions of the input sentence all match propositions stored in one's semantic memory, one says "yes" to the question. If one or more of the propositions in the input sentence are contradicted by a proposition stored in semantic memory, one says "no." If any of the input propositions can neither be found in semantic memory nor contradicted, one might guess either "yes" or "no" or answer "don't know" (if such a response is permitted).

A *wh*-question asks whether the components of the input sentence already exist in semantic memory with an additional component that constitutes the answer to the question. To answer the question, "When did Warren catch the walleye?" one first attempts to find all the components of the input question as an existing node structure in semantic memory (recognition). That is to say, one attempts to find a node structure containing the fact "Warren caught a walleye." Then one attempts to fill in the blank represented by the question word—*when*—by retrieving one or more time concepts, phrases, or propositions associated with the recognized node structure.

Asking and answering questions is an extremely good way to learn. This Socratic or dialogue method of instruction has been an education ideal for a very long time. We very much want to encourage students to learn by actively asking questions. When you read a book or listen to a lecture, you will greatly increase what you learn by actively thinking of questions you want the book or the lecturer to answer. What makes a personal tutor so terrific for learning is being able to ask lots of questions and get answers to just what you do not know and want most to learn at that moment. No one knows for sure why asking questions is so beneficial for learning, but one plausible answer is contained in the previously discussed theoretical analysis of *wh*-question answering: To ask (or answer) a *wh*-question, one must have built a semantic memory node structure that includes a large part of what is necessary to encode (or retrieve) the answer. If we ask the question, "What constituent provides the best cue for recall of a proposition?" we need already to have established a node structure, such as that shown in Figure 10-5. This means that when we ask that question, we have already established six of the eight higher-order nodes and 12 of the 16 vertical associations necessary to encode the answer, "The subject constituent provides the best cue for recall of a proposition." Asking questions tends to insure that we will store the complete answer in semantic memory rather than just part of the answer, because so much of the acquisition process has already occurred.

free of the potential for error. Human beings undoubtedly store the general proposition that birds fly, despite the fact that they have also stored that particular birds cannot fly. Conflicting conclusions may be avoided by following the general rule that specific information takes precedence over general class information whenever the two are in conflict.

Expansion

Imagine that you overheard someone say, "Our lawyer bailed John out this morning." Human beings almost automatically expand upon such information by inferring such things as "John was arrested last night and spent the night in jail," or perhaps that "John committed a crime." Such expansion inferences have a much greater than chance probability of being correct.[17]

Transitive Relations (Linear Orderings)

"If John is taller than Bill and Bill is taller than Sam, then John is taller than Sam." It is still an open question whether inferences involving transitive relations are performed in verbal semantic memory or in a nonverbal image memory. In image memory each item in a linear ordering might have a certain absolute size that we compare in the same way we compare perceptual images to determine which is bigger, taller, happier, etc. One piece of evidence that appears to support some type of processing of this sort is Moyer's finding that decisions regarding remote pairs in a linear ordering, such as "Is a tiger bigger than a flea?," are faster than decisions regarding close pairs, such as "Is a tiger bigger than a lion?"[18]

COMPUTER-ASSISTED INSTRUCTION AND SEMANTIC MEMORY

Computers can be extremely useful, albeit still very expensive, vehicles for instruction.[19] The most typical use of a computer for direct instruction is somewhere between a textbook and a human teacher. The unit of instruction is a *frame*, which is usually an amount of material that can be displayed on the TV screen that forms a part of a student's terminal. The student's terminal also may include an audio output device, and it almost always includes something like a typewriter keyboard for responding to the computer's questions or asking questions of the computer. Frames may be of a number of types: information-giving frames, question-asking frames, answer frames, directional frames ("return to your classroom," "choose the lesson you wish to work on today"), and mixtures of these types. The computer will present information, ask a question, wait for a response, decide whether the answer is correct, and provide an answer frame stating that the answer was correct or that it was wrong and, often, why it was wrong. Then the computer will decide the information or question frame to present next.

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[17] The identification of these and many other types of inferences owes a great deal to the work of Roger Schank and Charles Rieger, especially in R. C. Schank and C. J. Rieger, "Inference and the Computer Understanding of Natural Language." A.I. Memo 197, Computer Science Department, Stanford University, 1973.

[18] R. S. Moyer, "Comparing Objects in Memory: Evidence Suggesting an Internal Psychophysics." *Perception and Psychophysics*, 1973 (13), 180-84.

[19] R. C. Atkinson, "Teaching Children to Read Using a Computer." *American Psychologist*, 1974 (29), 169-78. P. Suppes and M. Morningstar, "Computer-Assisted Instruction." *Science*, 1969 (166), 343-50.

There are several advantages to computer-based instruction. First, the computer evaluates the student's answer and can give individually appropriate *feedback* concerning the type of mistakes made by a particular student. Programmed texts can approach this kind of flexibility by listing all the classes of answers to a question and the feedback to the student appropriate for each answer, but this is clumsy and slow. A classroom teacher also has fairly severe limits on the amount of individually appropriate feedback he or she can give, since many students must be taught at once. A personal tutor can be either better or worse than a computer in providing individualized feedback, depending on the quality of the tutor and of the computer's instructional program. Second, the computer has considerable power to make decisions regarding the optimal scheduling of instruction for each individual: how to sequence the frames, what to review and when, what to skip, etc. Atkinson has demonstrated that such optimization can substantially increase learning speed.[20] Textbooks have much less power to optimize the scheduling of instruction, and classroom teachers are probably also less effective at this.

Third, administrative chores such as testing, grading, and record keeping are performed very efficiently by computers.

Computer-based instruction is sometimes deficient in the extent to which teachers have explicitly programmed their knowledge of a subject or of pedagogical technique (or both) into the computer. Computer-assisted instruction can be excellent, if good teachers put much thought into the preparation of the instructional frames and the executive control program, and if the resulting system is tested and modified where it proves to be deficient. If these conditions are not met, such instruction can be very poor.

The fundamental deficiency of most computer-based instructional systems today is in its capacity to answer students' questions. We said earlier that a dialogue method of instruction, where students can ask questions about a subject and get appropriate answers immediately, is ideal for many purposes. Certainly it encourages a more active, creative, problem-solving approach to education, and this can be very useful in later life. Some beginnings have been made toward developing such question-answering programs for use in teaching,[21] but the development of question-answering programs depends on development of artificial semantic memories in computers, so that they can encode knowledge in a form suitable for understanding questions. A computer cannot answer a question unless it can recognize what the question is about. As we learn more about the structure of semantic memory and how we match the constituents of a question to nodes in semantic memory, we will be able to construct dialogue-teaching programs that are effective artificial analogues to having a tutor for each student.

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[20] R. C. Atkinson, "Ingredients for a Theory of Instruction." *American Psychologist*, 1972, (27), 921-31.

THE ACQUISITION OF CONCEPTS

Constituent and Propositional Meaning

Concepts occupy an intermediate position in the verbal modality. On the one hand, a concept can be thought of as the top unit of structural representation for the set of constituent attributes that activate that concept. On the other hand, a concept is the lowest unit of representation in meaningful semantic memory. The meaning of a concept is a combination of these sets of constituent attributes that activate it from below and the propositions in which the concept is incorporated that can activate it from above.

One hypothesis regarding the distinction between concrete and abstract concepts is in terms of the relative emphasis upon constituent versus propositional determinants of the meaning of a concept. Concrete concepts can be directly activated by one or more sets of lower-level constituent attributes, while very abstract concepts may be only indirectly activated from sensory input by means of prior activation of phrase or propositional representatives that in turn activate the abstract concept representative. Of course, abstract verbal concepts can be activated by the sensory attributes of their name, but they may not be activated by perceptual referential stimuli. By contrast, a more concrete concept such as *dog* can be activated by both auditory or visual verbal input (the name *dog*) and by referential stimuli, such as the sight of a dog or the sound of barking.

Discussions of concept acquisition by either children or adults have tended to emphasize the chunking of lower-level sensory constituents to form a concept representative, but a balanced treatment of concept acquisition would undoubtedly place at least as much emphasis upon acquisition of concepts by way of incorporation in relevant propositions. Children probably learn the meanings of many words from simply hearing or seeing them used in a variety of different sentences. In such cases, the concept does chunk the lower-level sensory attributes in the name, but the referential meaning of the concept may be encoded largely indirectly by memory for the propositions in which the concept is embedded. After I learned to read and began reading one book after another, my mother would frequently chastize me for not looking up in the dictionary words that I did not understand. Despite her repeated admonitions to look up new words in the dictionary, I almost never did it. Nevertheless I acquired a large vocabulary, undoubtedly much more quickly than I could have by following her advice or by asking her what words meant.

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[21] J. A. Swets and W. Feurzeig, "Computer-Aided Instruction." *Science*, 1965 (150), 572-76.

Much of the meaning of both concrete and abstract concepts probably comes from above by way of the propositions of which the concept is a part. However, virtually all of the work on concept learning has emphasized the view of concepts as logical functions of their lower-level constituents. All one can do is to keep in mind that such a view probably represents no more than half of the complete story.

Methods of Concept Learning

Concept learning is used to include everything from what a child does in learning the meanings of different words to what college students engaged in sophisticated inferential problem solving do to figure out the rule that classifies some complex forms into one geometric concept or another. The psychological processes involved in these two types of concept learning are undoubtedly very different. This difference has been recognized by most of the researchers in the concept-learning area, and they have distinguished a number of different methods of concept learning.

The most basic distinction among methods of concept learning is probably closely related to the distinction between constituent and propositional levels of concept meaning. These appear to be two basic classes of methods for concept learning: *observation* and *inference*. Observation, the more basic method, is the primary method used by young children, but it is also used by adults in situations where the instances to be classified differ on a very large number of dimensions that are not specified to the subjects, which results in little or no opportunity to draw logical conclusions concerning the nature of the concept. Inferential concept learning occurs when the examples of the concept differ on a small number of dimensions that are clearly explained to the subject, and when the type of concept is also clearly explained. This makes it possible for people to draw logical conclusions about the nature of the concept from a small number of examples or nonexamples. For inferential concept learning, subjects should have sufficient time to do the kind of logical thinking required to draw inferences concerning the concept. Inferential concept learning depends heavily upon the use of propositions already stored in semantic memory that encode the rules of logical reasoning.

who were exposed to a wide variety of different characters containing the common element did better than those who trained with a small number of characters. Presumably a larger set of characters conveys more information concerning the components of each character that are irrelevant to the concept and focuses attention on the relevant common component.

The common element in the examples of Hull's concepts were physically identical in every respect. Variations were created merely by the *addition* of extra elements to the character. In other concept-learning tasks there is a basic element, but it can be altered by *deletion* of some of its component parts or by systematic distortion around a central value. Following the terminology of Attneave, Posner, and Keele, the basic element in such concepts will be called a *prototype* or *schema.*[23]

Posner and Keele used material consisting of nine dots to construct several different prototype patterns, then they produced distortions of each by randomly moving the component dots various distances from their original position in the prototype. In one critical condition, subjects were given only distorted versions of each prototype, which they learned to classify with a single name, without ever seeing the original prototype. Subjects were then given new patterns to classify that included the previous examples as well as new distortions and the prototype itself. Subjects who had rote learned the characteristics of each example separately should show greater accuracy of classification of the original examples than of new distortions or of the prototype itself. In fact, subjects sometimes classified prototypes as accurately as the original examples, and in all cases more accurately than new distortions that were constructed to be as different from the originally learned examples as the prototype. Thus it would appear that subjects can extract a central prototypical definition of a concept solely on the basis of various distortions of the prototype, provided the distortions are not too great.

Posner and Keele also found that concepts learned in this way were defined not only by their central prototype but also by some knowledge of the degree of variability consistent with classification as an example of the concept. Evidence for this is that subjects exposed to a set of example patterns that exhibited little variation from the prototype were less likely to classify highly distorted new patterns as examples than subjects exposed during original learning to patterns that exhibited greater variation from the prototype.

It is still not clear exactly what is learned when a subject learns a pro-

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[23] F. Attneave, "Transfer of Experience with a Class-Schema to Identification-Learning of Patterns and Shapes." *Journal of Experimental Psychology*, 1957 (54), 81-88. M. I. Posner and S. W. Keele, "On the Genesis of Abstract Ideas." *Journal of Experimental Psychology*, 1968 (77), 353-63. M. I. Posner and S. W. Keele, "Retention of Abstract Ideas." *Journal of Experimental Psychology*, 1970 (83), 304-8. R. Hyman and N. Frost, "Gradients and Schema in Pattern Recognition," in P. M. A. Rabbit (ed.), *Attention and Performance*. Vol. 5. New York: Academic Press, 1974.

Observational concept learning. The simplest type of concept is one in which all the examples contain a common element. Hull studied observational concept learning by classifying a large number of Chinese language characters into different categories (concepts) on the basis of certain visual elements. The subject's task was to learn to respond with the correct nonsense syllable to each Chinese character in the set. Figure 10-6 illustrates the material used in Hull's experiment. The task was presented as rote learning, without any instruction regarding the possibility for learning the correct response on the basis of common elements possessed by all examples of each category. There was essentially no opportunity to acquire concepts by a logical reasoning or problem-solving process. Nevertheless after a large number of trials subjects could correctly classify previously seen characters and new characters as well.[22] Thus the subjects did learn the concepts by observation, in a manner that may be similar to the way young children and even adults learn concepts in the natural world. Indeed, many subjects who could correctly classify characters could not point out the common elements. Even when subjects were pretrained on a task that involved copying the common element out of context, they performed no better in the subsequent concept-learning task than subjects given no pretraining on the common elements. But if the common elements were presented in the context of the remainder of the characters and painted in red to attract attention, then concept learning was facilitated. Finally, those

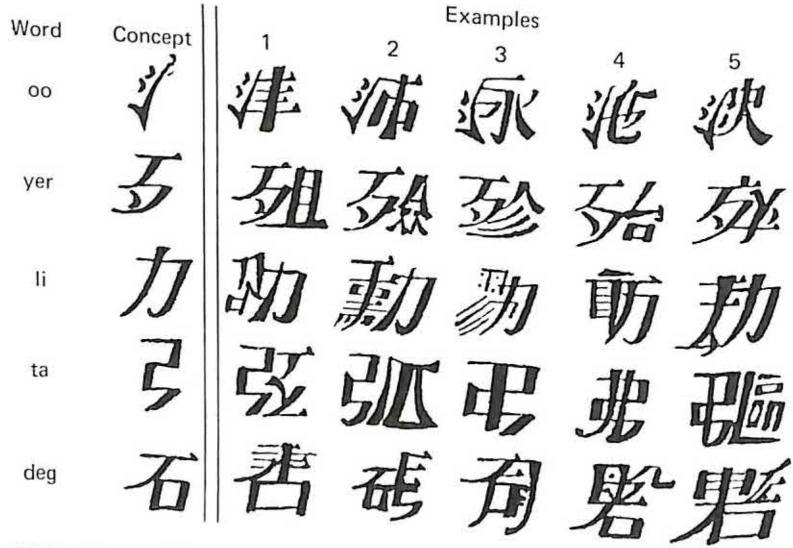

Figure 10-6. Some of the concepts and examples used by Hull.

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[22] C. L. Hull, "Quantitative Aspects of the Evolution of Concepts: An Experimental Study." *Psychological Monographs,* 1920 (28), Whole No. 123.

totype in conjunction with some notion of the acceptable types and degrees of transformation of that prototype. Some theorists deliberately contrast definition of a concept in terms of a prototype with definition of a concept in terms of sets of component attributes or features. When a concept is defined by a prototype, sometimes it may be possible to find a conjunction of attributes that characterize that prototype. Alternatively, many concepts may be learned by means of a multiplicity of different prototypes. In such cases a concept would be a disjunction of various conjunctions of attributes. That is, an instance is an example of a concept if it possesses one set of attributes or some other set of attributes or some other set of attributes, etc.

Inferential concept learning. The classic investigation of inferential concept attainment is that of Bruner, Goodnow, and Austin. Subjects were given artifical geometric stimuli differing in a number of dimensions such as shape, color, number of borders, number of figures, and so on. The possible values for a stimulus on each dimension were specified, and subjects were explicitly instructed regarding possible rules for defining an instance as an example or nonexample of a concept. For example, subjects might be told that the concept was a simple conjunction of one or more relevant attributes, where an attribute was a particular value of a dimension. A typical concept might be all stimuli containing two red squares. Such a concept has three relevant dimensions: the number, shape, and color of the figures. Bruner, Goodnow, and Austin used Harvard students as subjects.

As a result of all these characteristics, it should come as no surprise that the methods used by the subjects were highly inferential and completely different from the methods used by children or by adults under other conditions. Bruner, Goodnow, and Austin classified their subjects' methods of inferential concept attainment into two categories: *scanning* (hypothesis testing) and *focusing* (inferences concerning relevant and irrelevant dimensions). Scanning consists of forming an hypothesis, usually from one example, about the concept, testing that hypothesis against subsequent examples and nonexamples, rejecting it when it fails, and selecting a new one, until arriving at a concept that seems to fit all the examples and nonexamples.

The focusing method is logically more efficient. In the simplest focusing method, subjects might compare two examples of a conjunction and infer that all the attributes that differ in the two examples must be irrelevant to the concept. Using the focusing method for conjunctive concept attainment, subjects can also compare an example and a nonexample of the concept that differ in only one attribute and infer that the differing attribute must be relevant to the concept. The frequency of focusing, as opposed to scanning, methods is greater for more intelligent subjects and for subjects with greater practice in concept-attainment tasks.[24]

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[24] J. S. Bruner, J. J. Goodnow, and G. A. Austin, *A Study of Thinking*. New York: Wiley, 1956.

Attention and Concept Learning

In both observational and inferential concept learning, attention plays an important role. Subjects do not pay equal attention to all of the attributes of examples and nonexamples. Hull's study of observational concept learning demonstrated that drawing attention to the common element by painting it in red facilitated concept learning. In the scanning method of inferential concept learning, subjects typically acquire information concerning the attributes that are relevant according to the hypothesis they currently hold and learn little else from presented examples and nonexamples. In the focusing method, subjects draw conclusions concerning the relevance or irrelevance of the attributes that change from one example to another and logically draw few if any conclusions concerning the attributes whose relevance has not yet been determined.

Studies by Bourne and his associates have demonstrated that increasing the number of either relevant or irrelevant attributes increases the difficulty of concept learning. Such findings are predictable on a number of hypotheses, but limitations of attentional capacity provide the most plausible explanation for them. The more irrelevant dimensions there are, the more likely the subject is to pay attention to an irrelevant dimension rather than to a relevant one. The more relevant dimensions there are, the more dimensions the subject has to pay attention to in order to learn the concept.[25]

Bower and Trabasso rather definitively demonstrated the importance of attentional processes in concept learning. First they observed that subjects doing concept learning typically performed at chance, then suddenly increased to nearly 100 percent correct in their classification of instances as examples or nonexamples. Furthermore, if the correct values of the relevant attributes were shifted during the presolution period, subjects learned the new shifted concept as rapidly as subjects that had never been shifted. Such results suggest that under these conditions nothing is learned about the correct values prior to directing attention to the relevant attributes.

Finally, concepts can be defined by means of redundant relevant dimensions. For example, the examples of a concept might all be blue circles, but since circles are never presented in any other color but blue, and since blue is not used as the color of any other form, the two dimensions —blue and circles—are redundant in that the subject need only learn the correct value of one of them in order to solve the concept-learning task. Trabasso and Bower found that most subjects base their response on only one attribute and are typically unaware of the other relevant attribute.[26]

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[25] L. E. Bourne, Jr., "Effects of Delay of Information Feedback and Task Complexity on the Identification of Concepts." *Journal of Experimental Psychology*, 1957 (54), 201-7. R. Bulgarella and E. J. Archer, "Concept Identification of Auditory Stimuli as a Function of Amount of Relevant and Irrelevant Information." *Journal of Experimental Psychology*, 1962 (63), 254-57. P. G. Kepros and L. E. Bourne, Jr., "Identification of Biconditional Concepts: Effects of Number of Relevant and Irrelevant Dimensions." *Canadian Journal of Psychology*, 1966 (20), 198-207. R. C. Haygood and M. Stevenson, "Effects of Number of Irrelevant Dimensions in Nonconjunctive Concept Learning." *Journal of Experimental Psychology*, 1967 (74), 302-4.

Types of Concepts and Attributes

Most concept-learning problems have used *conjunctive* concepts—that is, examples of the concept possess a combination of attributes, and nonexamples lack one or more of these attributes. However some experiments have used *disjunctive* concepts, in which examples possess one attribute or another attribute or another attribute, etc. Disjunctive concepts can use either the *inclusive-or* (*A* or *B* or both) or the *exclusive-or* (*A* or *B* but not both). More complex concepts are possible, such as disjunctions of conjunctions of elements. Finally, other logical functions, such as implications (if *A* then *B*) can also form the basis for defining examples of a concept.

A number of studies that have compared the difficulty of learning different logical types of concepts are in virtual agreement that conjunctive concepts are the simplest type to learn, although Bourne has demonstrated that highly practiced subjects can eventually become as proficient with disjunctive and implicational concept learning as they are with conjunctive concept learning.[27] Neisser and Weene suggest that human beings use only three basic logical operators, conjunction, inclusive disjunction, and negation.[28] All concepts can be defined in terms of these three basic operators and the order of difficulty in learning concepts for inexperienced subjects appears to be reasonably well predicted by complexity as measured by the number of such basic operators required to define the concept.

Negation

The role of negation in concept learning has been studied in two different senses. In investigations that have studied how much subjects can learn from examples as opposed to nonexamples of a concept, the results have generally shown that more is learned from examples than from nonexamples.[29] With most real life concepts, though, nonexamples generally provide less information than examples, but when the information in nonexamples is controlled so as to be equal to that in examples, subjects initially learn less from nonexamples but with practice can learn from nonexamples as efficiently as from examples.[30] In natural concept learning, nonexamples probably play the role of preventing overgeneralization. The hypothetical child who calls every man "Daddy" has presumably acquired a concept with too few relevant attributes. Misclassifications of this type are generally corrected, so that the differentiating characteristics of other men are associated with the negation of the concept "Daddy."

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[26] G. Bower and T. Trabasso, "Reversals Prior to Solution in Concept Identification." *Journal of Experimental Psychology*, 1963 (66), 409-18. G. Bower and T. Trabasso, "Concept Identification," in R. C. Atkinson (ed.), *Studies in Mathematical Psychology*. Stanford: Stanford University Press, 1964. T. Trabasso and G. Bower, "Presolution Reversal and Dimensional Shifts in Concept Identification." *Journal of Experimental Psychology*, 1964 (67), 398-99. T. Trabasso and G. Bower, *Attention in Learning*. New York: Wiley, 1968.

[27] L. E. Bourne, Jr., "Learning and Utilization of Conceptual Rules," in B. Kleinmuntz (ed.), *Memory and the Structure of Concepts*. New York: Wiley, 1967.

[28] U. Neisser and P. Weene, "Hierarchies in Concept Attainment." *Journal of Experimental Psychology*, 1962 (64), 644-45.

Negation can also play a different role in concept formation, in that concepts can be defined in terms of the absence of certain attributes as well as the presence of these attributes. Under at least some conditions, it appears that concepts requiring the absence of an attribute can be learned as quickly as concepts requiring the presence of an attribute.[31] The most important condition for obtaining this result is probably that the subject initially have some reason to expect the absent attribute to be present. This occurs when the number of attributes is small and the prohibited attribute occurs in nonexamples of the concept. The negation of something is probably only represented in the human mind when there is reason to expect its positive occurrence and that expectation is not satisfied. Negative attributes can only be learned when there is some reason to expect them.

The role of negation in concept learning points up the likely possibility that concept learning depends as much upon associating similar nonexamples to the negation of the concept (for instance "not Daddy") as upon associating examples to the concept representative ("Daddy"). In addition, the attributes associated to a concept or to its negation may be negations of attributes (negative attributes) as well as positive attributes.

Developmental Trends

As Piaget has emphasized, the first concepts that children learn appear to be concrete objects and the actions that apply to such objects.[32] Children use words such as *Mama, milk, apple, drink,* and *eat* before they use property adjectives or adverbs such as *white, round, quickly* or *red* or superordinate noun and verb concepts such as *person, fruit,* or *consume*. Furthermore, concepts that have to do with concrete objects, actions, or the properties of concrete objects or actions tend to be acquired before more abstract concepts, which are not so closely linked to observable referents. There are many apparent exceptions to the notion that concepts more directly linked to concrete referents are acquired before more abstract concepts. For example, the words *good* and *bad* are used with reasonable propriety at an early age, although children's concepts of morality undergo many changes with age.

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[29] C. I. A. Hovland and W. Weiss, "Transmission of Information Concerning Concepts Through Positive and Negative Instances." *Journal of Experimental Psychology*, 1953 (45), 165-82. R. W. Schvaneveldt, "Concept Identification as a Function of Probability of Positive Instances and Number of Relevant Dimensions." *Journal of Experimental Psychology*, 1966 (72), 649-60.

[30] V. Freibergs and E. Tulving, "The Effect of Practice on Utilization of Information from Positive and Negative Instances in Concept Identification." *Canadian Journal of Psychology*, 1961 (15), 101-6.

[31] Neisser and Weene, "Hierarchies in Concept Attainment."

[32] J. Piaget, *The Construction of Reality in the Child*. (Translated by Margarate Cook.) New York: Basic Books, 1954.

This rasies the methodological point that conceptual development is very inadequately assessed by an inventory of the words in a child's vocabulary. When a child "overgeneralizes" the use of a word such as by calling all men "Dada," it does not necessarily indicate an overgeneralized concept. It might be that the child has developed a reasonably appropriate concept of "Daddy," but without any other name to attach to another man, he or she chooses to use the most appropriate word in his present vocabulary. The sight of a man may activate the concept "Daddy" more than it activates any other concept to which the child has learned a name and therefore the verbalization "Daddy." Young children, especially preverbal ones, have presumably learned many concepts for which they have not yet learned any reasonably appropriate word.

One thing we know for sure is that a child often does not have exactly the same meaning for words that an adult has. Hence, it is dangerous to use adult standards for classifying words concerning concreteness, abstractness, or other properties of the concepts represented by a word. A word that represents a very abstract concept for an adult may represent a much more concrete concept for a child. Only extensive testing of a child's use and comprehension of concepts can establish what concepts have been formed at any age. Nevertheless, it is possible to make a few very tentative statements concerning conceptual development that are relevant to the theory of concept representation.

First, whatever is meant by the statement that children's concepts are more concrete than adult concepts, it is not that children's concepts include only those adult concepts with the narrowest range of referential generality. That is, children do not acquire the concept of *Jonathan apple* before they acquire the concept *apple*, although children do usually acquire the concept *apple* before they acquire the concept *fruit*. From the viewpoint of referential generality, children appear often to enter conceptual hierarchies somewhere in the middle. Rosch speculates that the concepts learned first by a child (basic concepts) are the most general concepts that can be characterized by a single prototype.[33] According to this hypothesis, *apple* is a basic concept that is learned early by a child because apples are characterized by a single prototype but superordinates of apples such as *fruit* are not. The concept *apple* may be learned prior to *Jonathan apple* precisely because *apple* has greater referential generality (and therefore comes up more frequently), though both may be characterizable by prototypes.

This is a plausible hypothesis, that is largely consistent with the hypothesis that the concepts first learned by the child tend to be those concepts that are more frequently used by adults in their interaction with children. If adults tend to talk more about apples and to discuss fruits and Jonathan apples less frequently, there would be selective environmental pressure for a child to learn the concepts most frequently used by adults in communication with the child. Such environmental explanations leave unanswered the question of why adults prefer to communicate in terms of such basic concepts. Rosch's hypothesis provides an attractive explanation both for this adult use of basic concepts in communicating with children and for why it is functional for a child to learn first the basic concepts which are intermediate in referential generality.

Second, whatever is meant by the statement that children learn concrete concepts before they learn more abstract concepts, it is not that children learn the sensory attribute constituents of a concept before they learn any propositions in which the concept plays a part. As Piaget and many other cognitive development psychologists have emphasized, children tend early to learn the functions of objects in their environment and the actions that are relevant to those objects. A chair is something to sit on, a ball is something to throw, juice is something to drink, etc. It may be that these functional meanings of words are somehow encoded as sensory constituents of the concept, but it seems unlikely. What seems more plausible is that children at an early age are forming many propositions that embody concepts and that the meaning of a concept for a child is already determined as much by the learned higher-level propositions in which it is included as by learned connections to lower-level attribute constituents. Another reason for placing emphasis upon the propositional level of meaning at an early stage of cognitive development is that words standing for property concepts such as color and shape appear to be acquired substantially later than object and action concepts, which in some logical systems are composed of property constituents.[34]

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[33] E. Rosch, "Classifications of Real-World Objects: Origins and Representations in Cognition," in S. Ehrlich and E. Tulving (eds.), *Bulletin de Psychologie* (in press).

[34] S. Ervin-Tripp, "Some Strategies for the First Two Years," in T. E. Moore (ed.), *Cognitive Development and the Acquisition of Language*. New York: Academic Press, 1973, pp. 261-86.

THE ACQUISITION OF SYNTAX

There are a number of observations concerning the acquisition of syntax in children, but no reasonable theories and few theoretical principles in which we can have much confidence. Accordingly, here we will only make a general observation regarding the role of experience in this acquisition.

Some of the radical nativist followers of Noam Chomsky have asserted that the knowledge of snytax must be largely determined genetically, because the sentences that children hear are so incredibly complex it was alleged to be impossible for syntactic rules to be learned. Virtually all syntactic knowledge was thought to be built in, in the form of predispositions to learn certain rules and not others. It turns out, however, that the language spoken to children is considerably simpler than the language spoken to adults.[35] The language that mothers speak to children (called "motherese" by Newport) is under careful study by a number of developmental psycholinguists. More generally, adaptation by the speaker to the linguistic competence of the listener is a ubiquitous phenomenon of linguistic communication. Shatz and Gelman have shown that even four-year-olds adjust their speech to the age of the listener, using shorter and simpler utterances to a two-year-old than to an adult, irrespective of whether the four-year-old speaker has any younger siblings.[36]

It is not clear whether the simpler speech heard by younger children in any way facilitates the learning of syntactic rules, but most of the evidence on this matter has so far been largely negative.[37] Shorter and simpler linguistic utterences serve the function of eliciting more accurate immediate understanding, and this itself would constitute a sufficient reason for speaker adaptation to the linguistic capacities of the listener. However, it is still a very attractive hypothesis that the simple linguistic environment of young children plays an important facilitating role in the learning of linguistic rules.

The language spoken to children must not be too simple, both for optimum immediate communication and for long-term linguistic development. Shipley, Smith, and Gleitman found that children capable of two or more word utterances responded appropriately more often when given a request in a more complex adult form (for example, "Throw me the ball") than in the child's own simpler *telegraphic speech* ("Throw ball").[38] One also presumes that extensive use of baby talk or other oversimplified speech in talking to young children can retard speech development.

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[35] R. Brown and U. Bellugi, "Three Processes in the Child's Acquisition of Syntax." *Harvard Educational Review,* 1964 (34), 133-51. C. E. Snow, "Mother's Speech to Children Learning Language." *Child Development,* 1972 (43), 549-65. E. Moerk, "Changes in Verbal Child-Mother Interactions with Increasing Language Skills of the Child." *Journal of Psycholinguistic Research,* 1974 (3), 101-16. C. Fraser and N. Roberts, "Mother's Speech to Children of Four Different Ages." *Journal of Psycholinguistic Research,* 1975 (4), 9-16. E. Newport, "Motherese: The Speech of Mothers to Young Children," in N. J. Castellan, D. B. Pisoni, and G. R. Potts (ed.), *Cognitive Theory,* Vol. 2. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1976.

[36] M. Shatz and R. Gelman, "The Development of Communication Skills: Modifications in the Speech of Young Children as a Function of Listener." *Monographs of the Society for Research in Child Development,* 1973 (38), 1-38.

[37] Newport, "Motherese."

There is some experimental evidence supporting the role of experience in syntactic development. Cazden randomly assigned children in a day care center to different groups and found that children given a greater exposure to linguistic interaction with adults achieved greater gains in syntactic competence over a 12-week period than the control group. Furthermore, one type of linguistic experience produced greater gains than another kind, even though the two were equated for the absolute number of sentences.[39] Thus, experience does make a difference, but which characteristics of that experience are important is still unclear.

SUMMARY

1. Long-term memory for sentences is primarily of the meaning of the sentence and not of the particular words or grammatical structures used to convey the meaning, although it is possible to remember lexical and syntactic information.
2. The most basic unit of coding in semantic memory is the concept. A single concept node generally can be activated by many different words and phrases. A concrete concept can generally be activated by many different sets of cues associated with its referent(s), and these sets need not have any common physical attributes.
3. The specific node representation system can be extended to encode a conceptual compound (for example, a predicate or a context) and even an entire proposition (fact) by means of a single node linked by vertical associations to its constituents.
4. Semantic memory for a set of related propositions is encoded by means of the same network of overlapping propositions regardless of whether the propositions are presented in the same or different sentences. Human beings attempt to achieve semantic integration, which is the same network representation for propositions involving common concepts, regardless of when and how the various propositions are presented.
5. Answering questions requires recognition of the components of the question, for example, by identifying these components with existing

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[38] E. F. Shipley, C. S. Smith, and L. R. Gleitman, "A Study in the Acquisition of Language: Free Responses to Commands," *Language*, 1969 (45), 322-42.

[39] C. Cazden, "Environmental Assistance to the Child's Acquisition of Grammar." Unpublished doctoral dissertation, Graduate School of Education, Harvard University, 1965.

nodes in semantic memory. A yes-no question asks whether there is a network of nodes in semantic memory that matches the input statement. A *wh*-question (who, what, when, where) asks you to fill in a missing constituent by association to the recognized set of nodes representing the information in the question.

6. Acquisition of new propositions in semantic memory involves, first, recognizing the familiar portions of the input sentence (familiar concepts, phrases, and propositions) and, second, forming new vertical associations and chunk nodes linking these familiar nodes in new ways.
7. Most of the questions we can answer are not based on retrieval of a single proposition that is equivalent to the proposition partially or completely contained in the question, but require deductions from a single stored proposition or from two or more propositions stored in semantic memory.
8. The meaning of a concept is as much determined by vertically upward associations into higher-level propositional nodes (which relate a concept to other concepts) as by vertically downward associations to sets of lower-level constituent attributes.
9. A prototype is a set of attributes defining an ideal example of a concrete concept. Real examples differ from the prototype by having additional irrelevant attributes, and also, often, by minor deletions or modifications of relevant attributes.
10. There are two basic methods of concept learning: observation of many examples and nonexamples (induction of a prototype) and inference from a small number of examples and nonexamples (deduction using rules of inference stored in semantic memory).
11. Basic concepts are the most inclusive concepts (highest level of referential generality) that are characterized by a single prototype. These are the ones that children tend to learn first.
12. The role of experience and learning in the development of syntactic competence is still unclear. However, speakers adjust the complexity of their utterances to the linguistic competence of the listener. The shorter and simpler utterances spoken to young children may only facilitate immediate communication, but they may also facilitate the acquisition of syntactic rules.

11 Nonverbal Memory: Sensory Motor Skills and Imagery

OBJECTIVES

1. To point out that there is no special part of the brain where memories are stored. Rather memory is distributed throughout the perceptual, motor, and cognitive modalities of the brain.
2. To describe briefly the evidence from brain-damaged humans that supports a fundamental distinction between verbal and nonverbal coding in the mind.
3. To point out that the highest-level verbal and nonverbal modalities are specialized not for particular sensory or motor modalities, but for representing types of material (language, forms, spatial relations, music, etc.) that are largely independent of the modality of sensory input or motor output.
4. To distinguish between the *what* modality (images of the form of objects and operations on images) and the *where* modality (representatives of the locations of objects and movement operations on locations).
5. To describe some properties of the abstract spatial modality with respect to the representation of position and movement in motor memory and visual, tactile, and kinesthetic sensory memory.
6. To discuss changes in the spatial modality, focussing on sensory-motor learning in adaptation to visual rearrangement in humans (produced by distorting spectacles) and visual-motor development in young animals.
7. To discuss some properties of the imagery modality, including (1) the constituent structure of images, (2) the nature of a simple image and the synthesis of a complex image by successive imaging of its parts, (3) the relation between image size and image adequacy (clarity), and (4) the interaction between the imagery and verbal modalities.
8. To describe the phenomenon of eidetic imagery.

9. To distinguish between nondestructive image operations (scanning and zooming), which add to an image without actively destroying previously established image components, and destructive image operations (deletion, rotation, reflection, translation, magnification, minification, squashing, stretching, and tearing), which actively inhibit or negate some or all previous image components.
10. To describe mental rotation of images, including evidence that large-angle rotations are composed of smaller-step rotations, that image rotation speed is faster for two- than for three-dimensional forms, and that image rotation is a destructive operation.

As its name suggests, nonverbal memory is a concept defined negatively, by excluding verbal memory. It is not clear what all the examples of nonverbal memory have in common beyond the presumed lack of a significant verbal language component. After an introductory discussion of memory modalities, this chapter describes two nonverbal learning and memory modalities: the spatial modality and the imagery modality. There is no pretention to completeness of coverage (the musical modality is left out, for example), nor is there any really definitive evidence for distinguishing these two modalities. Discussion of the spatial modality is divided into two sections: one concerned with the representation of spatial position and movement and the other with sensory-motor learning. The discussion of image memory is divided into a section on images (including eidetic images) and a section on image operations.

MEMORY MODALITIES

Distributed Memory

The *lesion method* of identifying the function of a part of the brain is to observe the deficits that result from destruction of that part. This method achieved considerable success in gross identification of the psychological functions of different parts of the brain. Lesions in certain areas produce visual deficits, in other areas, auditory deficits, or somatosensory deficits, or motor deficits, and so on.

It was natural for some psychologists to suppose that one might find the area of the brain concerned with memory by cutting out different parts of it to see which lesion produced loss of memory. With one exception, these efforts proved a complete failure. To be sure there are areas which, when lesioned, will produce memory losses, but these losses are invariably accompanied by various perceptual, motor, and/or cognitive deficits. As a result of the work by Lashley and others, it appears fairly certain that there is no abstract memory modality separate from perceptual, motor, and cognitive representation.[1] Memory is distributed through the central modalities of the brain, and (with one exception) it does not appear to be possible anatomically to separate memory from other cognitive functions.

The one exception demonstrated by Milner and others, is that lesions of the mesial temporal and hippocampal areas of the human brain produce a relatively pure form of memory disorder independent of any perceptual, motor, or cognitive disability.[2] However, this disorder is not such as to suggest that the mesial temporal and hippocampal area is the storage area for memories in human beings. The memories that existed in patients before such a lesion are almost completely preserved, but the capacity to acquire new long-term cognitive memory traces is substantially diminished. The mesial temporal and hippocampal region appears to play a critical role in the formation of new long-term cognitive memory traces, but these traces are not stored in that area; rather, they appear to be stored in the same areas of the brain that are concerned with perceptual, motor, and cognitive functioning.

Questions regarding the modalities of memory are essentially equivalent to questions regarding the modalities of all other aspects of cognitive functioning. However, in discussing different modalities of representation it is important to remember that in addition to the memory traces formed within any given modality, there must clearly be associations between modalities. There has been little investigation of such cross-modality associations compared to within-modality associations. Nevertheless, it is logically important to remember that partitioning the brain into N representation modalities potentially partitions the brain into as many as N^2 memory modalities, representing all the ordered pairs of representation modalities.

Verbal and Nonverbal Memory

The anatomical division of the cerebral cortex into left and right hemispheres appears to be paralleled by a significant psychological difference, at least for right-handed individuals (for left handers the functional differentiation of the hemispheres is still unclear). For virtually all right handers the left hemisphere is specialized for verbal language, whereas the right hemisphere is specialized for nonverbal material such as images of complex geometric forms, memory for faces, chess, music, and the like. These conclusions derive primarily from two lines of evidence. First, as Milner and others have shown, lesions in the left hemisphere interfere primarily with verbal perception and memory, while lesions of the right hemisphere interfere with nonverbal information processing.[3] Second, Sperry, Gazzaniga, and their colleagues have recently studied the intellectual capacities of the left and right hemispheres separately in so called "split-brain" patients, patients who lack cortical communication between the two hemispheres because the corpus collosum, the neural pathway that connects the hemispheres, has been severed.[4]

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[1] K. S. Lashley, *Brain Mechanisms and Intelligence*. Chicago: University of Chicago Press, 1929. K. S. Lashley and L. E. Wiley, "Studies of Cerebral Function in Learning: IX. Mass Action in Relation to the Number of Elements in the Problem to Be Learned." *Journal of Comparative Neurology*, 1937 (57), 3-55.

[2] B. Milner, "Amnesia Following Operation on the Temporal Lobes," in C. W. M. Whitty and O. L. Zangwill (eds.), *Amnesia*. London: Butterworths, 1966, pp. 109-33.

Because virtually all of the sensory information from the right half of the visual field and from the right hand goes to the left hemisphere, while material from the left half of the field and the left hand goes to the right hemisphere, it is possible in split-brain patients to present a task for processing by a particular hemisphere, without help from the other and thus investigate the cognitive capabilities of each hemisphere separately. Such investigations show that the left hemisphere is able to identify verbally (by speaking or writing) any verbal or namable spatial figure presented to it. The right hemisphere is unable to speak or write, but can "match" spoken words of visually presented words or objects to objects touched with the left hand. Thus, both hemispheres are able to understand individual spoken or written words, but only the left hemisphere can understand syntactically structured propositions, whether spoken or written. Both hemispheres can identify simple visual images, but the right hemisphere is superior in processing complex images or sequences of images, jigsaw puzzles, and the like. It is not clear what purpose is served by localizing verbal and nonverbal functions in separate hemispheres. Presumably there are important differences in the higher-level organization of verbal concepts and nonverbal images that are facilitated by localization in separate hemispheres.

Sensory Modalities

Many people, including cognitive psychologists, often talk as if the modalities of the mind were to be identified with modalities of sensory input or motor output. Witness reference to the "visual modality" or the "auditory modality." It is important to point out that, for human beings, modality distinctions at the highest level of representation are based primarily on differences in the types of material represented and processed and are rather independent of the modality of input or output. Complex verbal input—whether the input is auditory, visual, or tactual and whether the output is by means of speech, writing, or palpation—is processed primarily in the left hemisphere. Analogously, whether form information is presented by means of visual, auditory, or tactual input and whatever output mode is used, complex forms are processed primarily by the right hemisphere. The distinction between these two cognitive modalities has very little to do with the mode of sensory input, and it is incorrect to identify the left hemisphere as the auditory modality and the right hemisphere as the visual modality, even though there may be some correlation in this regard.

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[3] *Ibid.*

[4] R. W. Sperry, "Hemisphere Deconnection and Unity in Conscious Awareness." *American Psychologist,* 1968 (23), 723-33. M. S. Gazzaniga, *The Bisected Brain.* Englewood Cliffs, N. J.: Prentice-Hall, 1970.

However, at lower levels there is clearly separate representation of the various modalities of sensory input and motor output. To the extent that the lower levels possess modifiable connections (have memory), there is some reality to the commonly held distinctions between visual and auditory memory.

Imagery and Spatial Coding

We have all had the experience of forgetting where we put something. The form properties of the lost object are well remembered, but its location in the world has been forgotten. This is because the form and the location of objects are dissociable types of information, as is intuitively clear to anyone once it is pointed out.

There may also be somewhat separate representations in the brain for forms (images) and spatial locations (including movements). As Fred Attneave puts it, there may be separate *what* (image) and *where* (spatial) systems. Attneave also observes that the *what* and *where* systems must have a close degree of interconnection, since we are capable of perceiving specific objects in specific locations.[5] Furthermore, the *what* system for form (images) must include at least the relative locations of the points, lines, and other constituents of a form in relation to each other. However, it seems reasonable to consider this local relative positional information (for image representation) to be distinct from the larger-scale information concerning the position and movement of objects in three-dimensional space (for spatial representation). The spatial system appears to have subcortical and bilateral cortical representation (representation in both hemispheres), with the right hemisphere representing location in the left visual field and the left hemisphere location in the right visual field.[6] By contrast there is considerable evidence that the image modality is located predominantly or exclusively in the right hemisphere for virtually all right handers and many left handers.

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[5] D. Ingle, G. Schneider, C. Trevarthen, and R. Held, "Locating and Identifying: Two Modes of Visual Processing: A symposium." *Pschologisches Forschung,* 1967-1968 (31), 44-62, 299-348. G. E. Schneider, "Two Visual Systems." *Science,* 1969 (163), 895-902. F. Attneave, "Apparent Movement and the What-Where Connection." *Psychologia,* 1974 (17) 108-20.

[6] Gazzaniga, *The Bisected Brain.*

SPATIAL POSITION AND MOVEMENT

Human beings code and remember the spatial positions of significant objects. They also appear to encode and remember certain characteristics of the changes of positions of objects (movement) such as speed, acceleration, duration, and extent of movement. Knowledge of position and movement for objects that are not a part of the body or in contact with parts of the body can only be given by exteroceptors, such as vision and hearing. Information regarding position and movement of bodily parts or of objects in contact with the body can be derived from visual, auditory, tactile, and kinesthetic sensory systems.

Much information concerning the position of body parts can also be derived from central motor representatives (motor outflow) that control the position of these parts, even in the absence of any sensory feedback. Indeed, in the case of an effector that has a constant load (constant weight to move), such as the eyeball, knowledge of its position (and therefore the direction of gaze) can be signalled entirely by the motor representatives that control the muscles of the eye. Thus, it is not surprising that the eye muscles of various species are thought to lack kinesthetic sensory receptors. All too often it has been assumed that knowledge of the position of some effector, such as the arm or the tongue, is given only by sensory feedback. While such sensory feedback does typically play an important role in knowledge and control of the position of various effectors, considerable knowledge and control of the position of bodily parts can be derived independent of sensory feedback, from central motor commands to the muscles.

Although spatial features must be separate for different sensory and motor modalities at some level of processing, all these sensory and motor systems may converge on some common abstract spatial representation modality that encodes position and movement. Such an abstract spatial modality would perform the useful function of integrating information regarding position or movement gained from any of these sources. Furthermore, as Laabs has demonstrated, information regarding position acquired through one modality (motor commands and kinesthetic feedback) can be interfered with by a processing task requiring the use of spatial information in a different modality (vision).[7] The integration of spatial information from different sensory and motor modalities and the fact that interference appears to be specific to the type of information, (rather than to the sensory or motor modality from which it was obtained) argue for a common cognitive representation of position and movement independent of the input mode. Nevertheless, most studies have concentrated on a particular sensory or motor modality, and this provides a convenient organization.

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[7] G. J. Laabs, "Retention Characteristics of Different Reproduction Cues in Motor Short-Term Memory." *Journal of Experimental Psychology*, 1973 (100), 168-77.

Visual Position and Movement

Kinchla and his colleagues have studied memory for the position of visual dots. Kinchla employed the psychophysical method of delayed comparison, which is a simple generalization of the standard successive comparison procedure used in psychophysics. In delayed comparison, a subject is first presented with a *standard stimulus* followed, after a variable delay, by the *comparison stimulus*. The subject is to judge the relation between the standard and comparison stimuli (in all respects or in one or more respects). The subject may be asked to make a *same-different judgment*, where sameness might be with respect to all dimensions or only a single dimension (such as vertical position). The subject might be asked to make a *directional judgment* concerning whether the comparison stimulus was higher or lower, greater or lesser, larger or smaller, to the right or the left, louder or softer, more or less intense, etc., than the standard stimulus.

In delayed comparison of dot position, Kinchla distinguished between knowledge of *absolute position*, which is the position of a dot within some unchanging frame of reference, and *relative position*, which is the position of a dot in relation to some other dot, object, or movable frame of reference.[8] In the encoding of spatial position, it is clear that we encode the position of an object in relation to one or more frames of reference. If these frames move with respect to one another, we can to some extent make separate judgments concerning the remembered position of an object with respect to each frame. Furthermore, we can remember a number of different locations for the same object at different times. It is not known whether this encoding of temporally or contextually specific associations between objects and locations occurs strictly within the spatial modality or involves associations between the spatial and the verbal propositional modality.

Tactile Position

Several investigators have studied memory for the position of stimulation on the skin, typically the arm or the hand. Although there are some methodological problems, by and large these studies demonstrate that memory for tactile position is relatively unaffected by performance of a verbal task during the retention interval.[9] Of course the retention of *verbal* information is adversely affected by performing verbal information-processing tasks during the retention interval.

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[8] R. A. Kinchla and L. G. Allan, "A Theory of Visual Movement Perception." *Psychological Review,* 1969 (76) 537-58. R. A. Kinchla, "Visual Movement Perception: A Comparison of Absolute and Relative Movement Discrimination." *Perception and Psychophysics,* 1971 (9) 165-71.

[9] J. C. Bliss, H. D. Crane, P. K. Mansfield, and J. T. Townsend, "Information Available in Brief Tactile Presentations." *Perception and Psychophysics,* 1966 (1) 273-83. E. Q. Gilson and A. D. Baddeley, "Tactile Short-Term Memory." *Quarterly Journal of Experimental Psychology,* 1969 (21) 180-84. E. V. Sullivan and M. T. Turvey, "Short-Term Retention of Tactile Stimulation." *Quarterly Journal of Experimental Psychology,* 1972 (24), 253-61. D. L. Schurman, I. H. Bernstein, and R. W. Proctor, "Modality-Specific Short-Term Storage for Pressure." *Bulletin of the Psychonomic Society,* 1973 (1), 71-74.

Some degree of verbal encoding of tactile stimuli would appear to be possible by means of phrases such as "near the wrist" and "near the elbow." However, delayed-comparison tasks that use a large number of possible points for the standard and comparison stimuli and relatively small differences between the standard and comparison stimuli appear to avoid significant contribution from verbal memory. One presumes there might be about five to seven discriminately different verbal categories into which the tactile stimuli could be categorized. If discriminative sensory memory is tested for adjacent points on a grid containing tens or hundreds of discriminably different points, the contribution of verbal memory for five to seven categories of points appears to be minimal. In psychophysical memory tasks subjects are generally able to remember much finger differences between stimuli than could be accomplished by verbal encoding alone. Nevertheless, verbal categorical memory may provide some contribution to psychophysical memory tasks, especially when only a modest number of different standard stimuli are used and the discrepancies between same and different comparison stimuli are relatively large.

Consideration of these matters appears to resolve some differences in experimental findings in the area of tactile memory. Studies that have assessed fine discriminations with large numbers of standard stimuli have not obtained interference from verbal information-processing tasks inserted in the retention interval. Interfering effects of verbal tasks on tactile position memory have been found only under conditions where relatively greater contributions from verbal memory would be expected because a smaller number of standard stimuli and grosser discriminations were used.[10]

That the tactile sense provides input to the same abstract spatial and image modalities to which the visual system provides input is suggested by the capacity of human beings to recognize both the nature and location of objects in space beyond the reach of their limbs through the use of a hand-held stick. If one picks up a stick and uses it to "feel" an object at some distance beyond one's reach, one can very frequently identify that object. Furthermore, if one knows the approximate length of the stick, one can determine the approximate location of the object in three-dimensional space. As James Gibson has pointed out, the objects "feels" as if it were at the end of the stick, not at the point where the stick touches the hand. Try this little experiment for yourself. Take a stick (a pencil or ruler will do), close your eyes, and open a drawer with several hard objects in it. Use your stick to feel around and identify the objects and their locations within the drawer, then visually check how accurate you were. Did the tactile experience feel as if it was taking place on your hand or out in space at the end of the stick? It should be noted that kinesthetic and motor information gained from tracing the object may also play a role in identification, but this only makes the present argument even more general. The spatial and image modalities are abstract and cognitive, not tied to particular sensory or motor modalities. It is a model of the real world, not a model of the pattern of sensation on the eye or skin.

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[10] Gilson and Baddeley, "Tactile Short-Term Memory." Sullivan and Turvey, "Short-Term Retention." Schurman, Bernstein, and Proctor, "Modality-Specific Short-Term Storage." E. V. Sullivan and M. T. Turvey, "On the Short-Term Retention of Serial, Tactile Stimuli." *Memory and Cognition*, 1974, (2) 600-606.

Kinesthetic and Motor Memory

The most extensive investigations of memory for position and movement have been those concerned with short-term memory for one-dimensional motor responses. A typical example of a one-dimensional motor memory task consists of having a subject move a lever from one position to another and then asking him or her to repeat that movement on another occasion.

Performance in this task confounds memory for terminal *position* with memory for the extent of the *movement*, if the subject begins from the same starting position in the recall or recognition memory test. Posner, Keele, and their students have devised experimental designs to test memory separately for each. For instance, by changing the starting position from the original to the test movement, one can instruct subjects to reproduce either the same extent of movement or the same terminal position. Subjects are able to perform with a fair degree of accuracy on both tasks, which indicates that terminal position and the extent of movement are both encoded and remembered.

Memory for position and memory for movement have been studied under conditions where subjects were able to view their hand while performing the movement rather than performing the movements blind. Accurate performance is possible in both conditions, but the combination of visual with kinesthetic and motor memory produces superior performance to kinesthetic and motor memory alone.[11]

Recognition tests have occasionally been used to assess motor and kinesthetic memory. In a recognition test a subject moves a lever until encountering a stop, then judges whether this movement was terminated at the same position or after the same extent of movement as the original movement, which was also terminated by a stop.[12] However, kinesthetic memory and motor memory have more typically been tested by a recall procedure in which the subjects attempt to produce a movement or terminal position identical to the original. In the latter case, accuracy is judged by both the average extent to which the recalled positions or movements deviate from the original positions or movements (constant error) and by the variability (standard deviation) of the subject's responses around that average recalled position or movement.

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[11] M. I. Posner and A. F. Konick, "Short-Term Retention of Visual and Kinesthetic Information." *Organizational Behavior and Human Performance*, 1966 (1), 71-86. M. I. Posner, "Characteristics of Visual and Kinesthetic Memory Codes." *Journal of Experimental Psychology*, 1967 (75), 103-7. S. W. Keele and J. G. Ells, "Memory Characteristics of Kinesthetic Information." *Journal of Motor Behavior*, 1972 (4), 127-34.

Performing movements or exerting forces during a retention interval adversely affects short-term memory for a movement or force, as measured by an increase in constant error or variability or both.[13] Laabs found that the interference effect of interpolated movements to increase response variability only occurred in memory for movement and not in memory for position, but interpolated movements produced assimilative constant errors in both cases such that the recalled movement or position changed in the direction of the interfering movement or position.[14]

Beginning with the study by Posner and Konick, another commonly observed difference between memory for position and memory for movement has been in the greater suspectibility of the former to verbal interfering tasks such as adding digit pairs, classifying digit pairs as high or low and odd or even, or counting backwards by threes with three-digit numbers during the retention interval.[15] The reasons for this are not clear, but the backward counting task (and perhaps the others) appears to involve some type of spatial as well as verbal representation. You can demonstrate this for yourself by attempting to write your name (which presumably involves some use of spatial modality) at the same time as you recite the alphabet (presumably a purely verbal task) or count backwards by threes starting from 947. The difference is dramatic. It is trivial to write your name accurately at the same time as you recite rapidly the alphabet or a familiar poem, song, or prose passage. *Try it.* By contrast, counting backwards by threes interferes substantially with writing your name, and this appears to be true even after one attains a high level of skill in the backward counting task. Counting backwards with three-digit numbers appears to involve a certain degree of place keeping for digits in the tens and hundreds positions while the digit in the unit position is being decremented, and such place keeping subjectively appears to involve a spatial code. Furthermore, although spatial position concepts appear to be involved in the backward counting task, no spatial movement concept appears to be involved. This may explain why such tasks interfere with position information and not with movement information.

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[12] B. H. Kantowitz, "Modality Effects in Recognition Short-Term Motor Memory." *Journal of Experimental Psychology,* 1974 (103), 522-29.

[13] R. L. Pepper and L. M. Herman, "Decay and Interference Effects in the Short-Term Retention of a Discrete Motor Act." *Journal of Experimental Psychology Monograph Supplement,* 1970 (83), 1-18. J. L. Craft and J. V. Hinrichs, "Short-Term Retention of Simple Motor Responses: Similarity of Prior and Succeeding Responses." *Journal of Experimental Psychology,* 1971 (3), 297-302. B. H. Kantowitz, "Interference in Short-Term Motor Memory: Interpolated Task Difficulty, Similarity, or Activity?" *Journal of Experimental Psychology,* 1972 (95), 264-74. E. A. Roy and W. G. Davenport, "Factors in Motor Short-Term Memory: The Interference Effect of Interpolated Activity." *Journal of Experimental Psychology,* 1972 (96), 134-37.

[14] G. J. Laabs. The Effect of Interpolated Motor Activity on the Short-Term Retention of Movement Distance and End-Location." *Journal of Motor Behavior,* 1974 (6), 279-288.

[15] Laabs, "Retention Characteristics." Rosner and Konick, "Short-Term Retention." Posner, "Characteristics." Keele and Ells, "Memory Characteristics."

Laabs has shown that interpolating a spatial relations test during the retention interval interferes with memory for both location and movement information. Spatial relations tests appear to involve both positional and movement concepts, since judging the identity (or some other relation) of two complex objects often requires mental translation and rotation operations. Thus, when the interference task contains both positional and movement concepts, there is interference with memory for both. Since Laabs used blind lever-positioning movements and the spatial relations test was visual rather than kinesthetic-motor, the experiment also demonstrates the abstract cognitive character of spatial memory, independent of modality of input.[16]

There is little doubt that visual input is in some sense the most precise and dominant form of input to the cognitive spatial modality, but a variety of other sensory and motor channels contribute as well. High-level cognitive modalities are not specific to the mode of input, but to the type of information represented.

SENSORY-MOTOR LEARNING

Adaptation to Lateral Visual Displacement

Over a century ago Helmholtz began a line of investigation that is still actively studied, concerning the adaptability of human beings to distortions of the visual world. The most commonly studied form of visual rearrangement has been a simple lateral displacement of the visual field, say ten degrees, that can be produced by special prismatic spectacles. Once one puts on such spectacles, one's initial visually guided movements are inappropriate, since what appears to be straight ahead is actually ten degrees to the left for prism spectacles that displace the visual field ten degrees to the right. After a relatively short time, on the order of minutes or tens of minutes of active, visually guided movement, one adapts to such lateral displacement and now makes relatively accurate visually guided locomotory or reaching movements.[17]

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[16] Laabs, "Retention Characteristics."

Adaptation to Other Distortions

Successful sensory-motor adaptation can also be demonstrated to rotation (tilt) of the visual field, up-down inversion, right-left reversals, magnification, minification of objects in the visual field, and split-field prism spectacles, where the upper half of the visual field might be displaced to the left and the lower half of the field unchanged, such that straight lines have a displacement at the horizontal boundary between the top and the bottom half of the field. Subjects wearing such split-field prisms learn to make automatic eye movements at the boundary between the top and the bottom half of the field to follow straight edges that cross the boundary. They can also successfully adapt their reaching and locomotory movements depending upon whether their direction of gaze is through the top or bottom half of the prism. Adaptation to displacements, inversions, reversals, size-change, and split-field prisms indicates a substantial degree of plasticity in adult sensory-motor coordination.[18]

What Is Learned in Adaptation to Visual Rearrangement?

There are many theories of the mechanisms that underly such plasticity. One fairly neutral theory—Held's—is that what has changed is the relationship between visual input and the kinesthetic and motor system that controls limb movement.[19] In some sense, this general statement must be true. Another theory advocated by Harris, is that what has changed in this relationship is the felt position of the various parts of the body, including the arms, legs, head, and eyes, and that there is no change in the representation of visual input per se.[20]

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[17] H. von Helmholtz, *Treatise on Physiological Optics*, Vol. 3, translated and edited by J.P.C. Southall. New York: Dover, 1962. G. M. Stratton, "Vision Without Inversion of the Retinal Image." *Psychological Review*, 1897 (4), 341-60, 463-81. See review by C. S. Harris, "Perceptual Adaptation to Inverted, Reversed, and Displaced Vision." *Psychological Review*, 1965 (72), 419-44.

[18] H. Mikaelian and R. Held, "Two Types of Adaptation to an Optically Rotated Visual Field." *American Journal of Psychology*, 1964 (2), 257-63. S. M. Ebenholtz, "Adaptation to a Rotated Visual Field as a Function of Degree of Optical Tilt and Exposure Time." *Journal of Experimental Psychology*, 1966 (72), 629-34. Harris, "Perceptual Adaptation." W. Epstein and C. L. Morgan-Paap. "The Effect of Level of Depth Processing and Degree of Informational Discrepancy on Adaptation to Uniocular Image Magnification. *Journal of Experimental Psychology*, 1974 (102), 585-94. I. Rock, *The Nature of Perceptual Adaptation*. New York: Basic Books, Inc., 1966. I. Kohler, "The Information and Transformation of the Perceptual World." *Psychological Issues*, 1964 (3), Monograph 12. H. L. Pick, Jr., J. C. Hay and R. Martin, "Adaptation to Split-Field Wedge Prism Spectacles." *Journal of Experimental Psychology*, 1969 (80), 125-32.

[19] M. E. Hardt, R. Held, and M. J. Steinbach, "Adaptation to Displaced Vision: A Change in the Central Control of Sensorimotor Coordination." *Journal of Experimental Psychology*, 1971 (89), 229-39.

Both theories appear to assume that at the highest level of spatial representation there are separate representations of visual positions and kinesthetic-motor (felt) positions. We have argued in the preceding section that this may not be true, and that there may be but one abstract cognitive representation of spatial position and movement at the highest level of the spatial modality. The issue regarding what is learned in adaptation to visual rearrangement is whether there is a change in the mapping of visual input onto this central spatial positional modality; a change in the mapping of tactile, kinesthetic, and motor inputs to the spatial modality; or changes in motor output. As we shall see, the answer to this general question appears to be that at different stages of adaptation to rearrangement and under different conditions, there can be changes in the mapping of all of these systems onto the spatial position system.

The most commonly chosen way to demonstrate support for Harris's hypothesis of changes in the felt position of parts of the body, such as the hand, is to ask the subject to point straight ahead with eyes closed, after a period of adaptation to laterally displacing prisms. Since the eyes are closed, such pointing is guided only by kinesthetic and motor cues. If the felt position of the hand has shifted, the subject will actually point to the right or to the left of the true straight ahead. Such changes in pointing are not always obtained under all conditions of visual adaptation, but they are very common, which indicates that under many conditions Harris is correct that an important component of visual adaptation is a change in the felt position of certain body parts, notably the arm and hand.[21] Changes in the felt position of the hand typically occur when the subject has adapted to the visual rearrangement primarily by making visually guided movements with his hand, with little or no head and body movement. When the subject has moved only his right hand during the adaptation period, there will often be no change in pointing straight ahead on the part of the left hand.[22]

In the present theoretical framework, Harris's change in the felt position of the right hand means a change in the mapping from tactile, kinesthetic, and motor cues associated with the right arm and hand onto the central spatial system. However under many conditions, especially after longer periods of adaptation and where the subject is permitted to make a variety of different movements and particularly gross locomotion, the change appears to be in the mapping of the visual cues onto the central spatial modality.[23] There is a very real sense in which the visual system dominates the central spatial modality, making it easier to change the tactile-spatial, kinesthetic-spatial, or spatial-motor mappings than to change the visual mapping.[24] However, as Helmholtz noted when he began this line of investigation, a change in the visual-spatial mapping is the most satisfactory compensation for optical rearrangement, and eventually something of this type appears to occur.

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[20] Harris, "Perceptual Adaptation."

[21] Harris, "Perceptual Adaptation." W. B. Templeton, I. P. Howard and D. A. Wilkinson, "Additivity of Components of Prismatic Adaptation." *Perception and Psychophysics*, 1974 (15), 249-57.

[22] Harris, "Perceptual Adaptation."

The mechanism by which it occurs is likely to be by modification of the system ordinarily used to combine information concerning retinal stimulation with kinesthetic and motor information concerning direction of gaze (including information concerning the position of the eye in relation to the head and the head in relation to the body). Under ordinary circumstances there is no fixed relationship between stimulation of a particular point on the retina and a particular location in space, as encoded in the central spatial modality. The position of visual stimulation on the retina must be combined with information concerning eye, head, and body position in order to determine the mapping of the retinal space onto "real space," as represented in the central spatial modality. Exactly how this is done is not clear, and it is therefore certainly not clear how this mapping might change under adaptation to visual rearrangement. In a very general sense one could still assert that Harris's position—that this type of adaptation involves a change in the felt position of the eyes in relation to the head or of the head in relation to the body, etc.—was correct. However, note that this felt position is intimately involved in the mapping of visual stimulation onto the central spatial representatives and thus is not a *purely* proprioceptive change.

Active and Passive Movement

Held and Hein demonstrated that active, self-produced movement greatly facilitates adaptation to visual rearrangement. Simply viewing one's arm as it is passively moved within the visual field often appears to be inadequate for producing adaptation to lateral displacement, even though this information is logically sufficient to establish a new correlation between seen positions and felt positions. However, considerable adaptation to visual rearrangement can apparently be achieved with passive movement, provided subjects are required to make judgments concerning the direction of objects or of the visible hand.

Furthermore, Held, Efstathiou, and Green have demonstrated that there must be a high degree of temporal contiguity between the movement and the resulting visual feedback in order for successful adaptation to occur. Delay of visual feedback (through complex means) by as little as 0.3 seconds, prevented adaptation to displacement.[25]

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[23] J. C. Hay and H. L. Pick, Jr., "Visual and Proprioceptive Adaptation to Optical Displacement of the Visual Stimulus." *Journal of Experimental Psychology*, 1966 (71), 150-58.

[24] I. Rock and C. S. Harris, "Vision and Touch." *Scientific American*, 1967 (216), 96-104.

Visual-Motor Development

The self-produced movement that is helpful in adaptation to visual rearrangement by adult human beings may be critical for the development of visually guided reaching and locomotion in young animals (kittens and monkeys have been studied). In one clever experiment, Held and Hein raised pairs of kittens from two to ten weeks of age in the dark, except for a daily three-hour period. During this three-hour period the kittens in each pair were yoked together in an apparatus in such a way that one kitten was free to move around inside a lighted cylinder while the other was carried passively about in a gondola. The kittens were linked mechanically in such a way that the visual experiences of the passively moved kitten were identical to that of the actively moving kitten. Despite equivalent visual stimulation, only the active kitten developed normal, visually guided paw placement and ability to discriminate depth.[26]

Furthermore, a kitten that moves in light while wearing an opaque collar that prevents it from viewing its limbs and body acquires the capacity for visually guided locomotion (avoiding obstacles, etc.) but is not able to visually guide its forelimbs to targets.[27] If the collar is arranged so that only one forelimb can be viewed, visually guided reaching is restricted to the limb that is viewed.[28]

IMAGERY

Think about some house you lived in for a considerable time. How many windows does it have? Where are they? What size and shape are they? How many doors does the house have? Where are they? Do the doors have windows in them or are they solid? What do the door handles look like? Chances are that you are able to answer most, if not all, of these questions and that to answer them your subjective experience is of recalling visual images and "seeing" the answer to the questions in those images.

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[25] R. Held and A. V. Hein, "Adaptation of Disarranged Hand-Eye Coordination Contingent upon Re-Afferent Stimulation." *Perceptual and Motor Skills,* 1958 (8), 87-90. H. L. Pick, Jr., and J. C. Hay, "A Passive Test of the Held Re-Afference Hypothesis." *Perceptual and Motor Skills,* 1965 (20), 1070-72. G. Singer and R. H. Day, "The Effects of Spatial Judgments on the Perceptual Aftereffects Resulting from Prismatically Transformed Vision." *Australian Journal of Psychology,* 1966 (18), 63-70. R. Held, A. Efstathiou, and M. Greene, "Adaptation to Displaced and Delayed Visual Feedback from the Hand." *Journal of Experimental Psychology,* 1966 (72), 887-91.

[26] R. Held and A. Hein, "Movement-Produced Stimulation in the Development of Visually Guided Behavior." *Journal of Comparative and Physiological Psychology,* 1963 (56), 872-76.

[27] A. Hein and R. Held, "Dissociation of the Visual Placing Response into Elicited and Guided Components." *Science,* 1967 (158), 390-92.

[28] A. Hein and R. M. Diamond, "Locomotory Space as a Prerequisite for Acquiring Visually Guided Reaching in Kittens." *Journal of Comparative and Physiological Psychology,* 1972 (81), 394-98. R. Held and J. Bauer, Jr., "Visually Guided Reaching in Infant Monkeys after Restricted Rearing." *Science,* 1967 (155), 718-20.

After long neglect in experimental psychology, there has been an upsurge of interest in mental imagery during the last decade. Because some narrow-minded *S-R* psychologists were at one time reluctant to admit the existence of mental imagery, numerous cognitive psychologists have engaged in experimental overkill merely to demonstrate the existence of an imagery modality separate from the verbal modality. Today we have perhaps a hundred alleged experimental demonstrations of the *existence* of imagery for every study that purports to say something concerning the *properties* of imagery. Here we shall concentrate on the properties of the imagery modality, but because the amount of evidence is limited, it should be understood that the conclusions reached here are largely speculative.

Constituent Structure

A simple geometric form such as (b) in Figure 11-1 is encoded at the level of primary visual cortex by nodes representing all of its constituent line segments. Various combinations of these line segments comprise simple forms that may be represented by single nodes in the image modality. The constituents of an image for a simple form would then be nodes representing all the lines and angles that compose it.

A more complex form, such as (a) in Figure 11-1, might have as its constituents all the lines and simpler forms that are contained in it, but this hypothesis has been demonstrated to be false. Human beings encode a complex form such as this by a set of constituents that does not include all the possible simpler forms contained in the figure. Stephen Reed investigated the constituent structure of forms by presenting a figure such as (a)

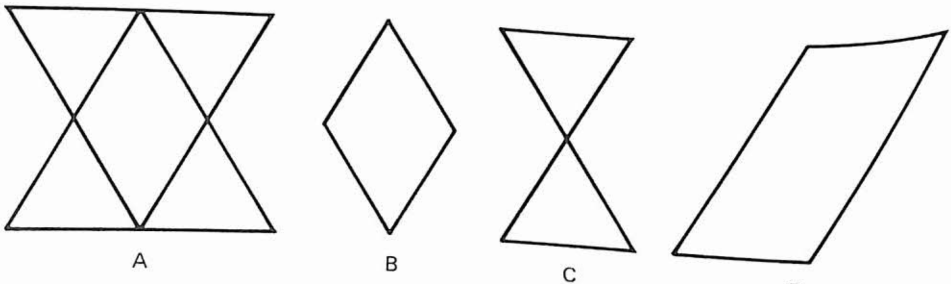

Figure 11-1. Figures (b), (c), and (d) are all contained in (a), but subjects appear to encode (a) using constituents such as (b) and (c), but not using constituents such as (d).

and a few seconds after removal of (a) presenting a figure like (b), (c), or (d) and asking subjects to judge whether (b) was contained in (a). Subjects were instructed to respond quickly in order to tap what had been directly encoded in the visual image, rather than to decide by a slower, inferential comparison process. Using this technique, subjects made rapid part-identification responses, but some simpler forms contained in the image were correctly identified much more frequently than others. For example, (b) and (c) were recognized as constituents of (a) almost two-thirds of the time, but (d) was recognized as a constituent of (a) only 10 percent of the time. Figure (d) is a closed geometric figure just as (b) and (c) are, and it is at least as simple and familiar as (c), if not more so. Finally, there are other images in which (d) is recognized as a constituent more rapidly than (c).[29]

One can conclude that a complex image such as (a) has a definite constituent structure that does not include all possible features and combinations of features equally, as a simple photograph theory of image representation might suggest. Rather the constituent structure of an image is selective, and the components selected depend in an as yet undetermined way upon the context in which they appear. That is, there is no simple rank ordering of image constituents such that a constituent higher on the rank ordering is more likely to be perceived in any complex image context than a constituent lower in the ordering.

Image Complexity

Images are more complex the more constituents they contain. Is the vividness of a visual image independent of visual complexity—that is, can we imagine all the constituents of a complex image as adequately as we can the constituents of a similar image? We might guess that when an image becomes sufficiently complex its parts cannot all be simultaneously activated in image memory and must be imaged in rapid succession. Hebb and others have put forward this hypothesis with respect to both acquisition and retrieval of complex images. In particular, Hebb suggests that the parts of a complex image are successively fixated during the initial acquisition (perception) of the image. Fixation of a particular part of a figure establishes a simple image for that part, and this is "glued together" with the simple images that result from fixations of other significant parts of the figure.[30]

There is substantial evidence to support the proposition that visual perception of a complex picture involves successive eye fixations on different, informationally rich portions of the picture. People do not stare at the center of a picture and build up an image from prolonged fixation focused on a single point.[31] In this regard image acquisition is sharply distinguished from acquisition of a visual sensory afterimage, for which a steady fixation on a single point is virtually essential. Thus, images are undoubtedly associative traces rather than nonassociative activity traces.

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[29] S. K. Reed, "Structural Descriptions and the Limitations of Visual Images." *Memory and Cognition,* 1974 (2) 329-36.

[30] D. O. Hebb, "Concerning Imagery." *Psychological Review,* 1968 (75), 466-77.

Such a conclusion is also supported by the fact that image memory can persist as long as verbal memory, sometimes for a lifetime. Loftus has demonstrated that recognition memory for pictures increases as a function of the number of fixations on a picture during learning and is independent of exposure time when the number of fixations is held constant. Initial learning of a complex picture generally depends primarily upon the number of fixations, provided study time per fixation is at least a few hundred milliseconds.[32]

Retrieval also appears to involve a revival of the image by means of successive generation of the parts. A number of investigators have demonstrated that recall of complex visual material is accompanied by eye movements. Furthermore, Hall showed that image recall is better when eye movements are permitted than when the subject is required to fixate a single point during retrieval of the image. There have been some failures to obtain such a relationship between eye movements and image retrieval, but they appear to be cases where the image was considerably simpler than in those cases where positive results have been obtained. Presumably the retrieval of a simple image is less dependent on or independent of successive generation of the parts.[33]

Basic questions yet to be answered are: What is the maximum number of image constituents that can be simultaneously activated? What is the maximum size of a *simple* visual image? How complex an image can be visualized without loss of vividness? The maximum complexity of the simple image might depend upon the nature and organization of the constituents rather than on their number. Perhaps we can only attend to one node in image memory at a time, but if that node stands for an entire image it might simultaneously activate all the constituent nodes with which it is associated. The degree of activation of each constituent node might vary inversely with the number of constituent nodes—that is, vividness of imagery decreases monotonically with increases in the number of constituents.

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[31] P. A. Kolers, "The Role of Shape and Geometry in Picture Recognition," in B. S. Lipkin and A. Rosenfeld (eds.), *Picture Processing and Psychopictorics*. New York: Academic Press, 1970, pp. 179-202.

[32] G. R. Loftus, "Eye Fixations and Recognition Memory for Pictures." *Cognitive Psychology*, 1972 (3), 525-51.

[33] D. F. Marks, "Individual Differences in the Vividness of Visual Imagery and Their Effect on Function," in P. Sheehan (ed.), *Function and Nature of Imagery*. New York: Academic Press, 1972. D. F. Marks, "Visual Imagery Differences and Eye Movements in the Recall of Pictures." *Perception and Psychophysics*, 1973 (14), 407-12. D. Kahneman, *Attention and Effort*. Englewood Cliffs, N. J.: Prentice-Hall, 1973. D. C. Hall, "Eye Fixations and Spatial Organization in Memory." *Bulletin of the Psychonomic Society*, 1974 (3), 335-37. G. Bower, "Mental Imagery and Associative Learning," in L. Gregg (ed.), *Cognition in Learning and Memory*. New York: Wiley, 1972.

There are experimental demonstrations supporting the hypothesis that increases in the complexity of the visual image decrease the adequacy of the image, as measured by the speed of making decisions regarding image constituents and their properties. Weber has invented a task that appears well suited for evaluating the relationship between image complexity and image adequacy. Subjects hear a word and are required to form a visual image of it. Several seconds later they hear a probe digit such as "3" which signals a subject to decide whether the third letter in the word is tall (b, d, f, g, . . . y) or short (a, c, e, . . . z). Since height is a visual property, we know that the subjects must be using image memory to make such a decision (though quite conceivably this memory is in the verbal modality, or at least in the same hemisphere as the verbal modality). When subjects have a relatively long time (four seconds), to construct the visual image, the speed of deciding whether a letter is tall or short is largely independent of serial position within both three- and five-letter words. For five-letter words there is some tendency for decisions regarding the last three letters to be somewhat slower than decisions regarding the first two. Weber and Harnish also performed a useful control of having subjects make the same decisions regarding letters in words that were visually presented and available at the time of the decision. Figure 11-2 presents their findings.[34] Hebb earlier proposed that one good test of whether decisions were based on a visual image of a word rather than on some verbal representation concerned whether the image could be read off backwards as rapidly as forwards.[35] The Weber and Harnish results demonstrate that this property does indeed hold for visual perception (as Hebb had assumed) and that the same property holds for visual images, provided the image is not too complex.

Three-letter words appear to yield a flat reaction-time function across serial position, but five-letter words do not. This suggests that all the constituents of a simple image are activated in parallel and that the maximum size of a simple image may be three or four letters. It is also interesting to note that for three-letter words decisions based on the image were slightly faster than decisions based on the percept, but that the reverse held for five-letter words. Weber and Harnish suggest that the maximum capacity for a simple visual image might be assessed by the maximum length word for which the image can be processed as rapidly as the percept. By this measure also, the maximum size of a simple image for words would appear to be on the order of three or four letters.

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[34] R. J. Weber and R. Harnish, "Visual Imagery for Words: The Hebb Test." *Journal of Experimental Psychology*, 1974 (102), 409-14.

[35] D. O. Hebb, *A Textbook of Psychology*, 2nd ed. Philadelphia: Saunders, 1966.

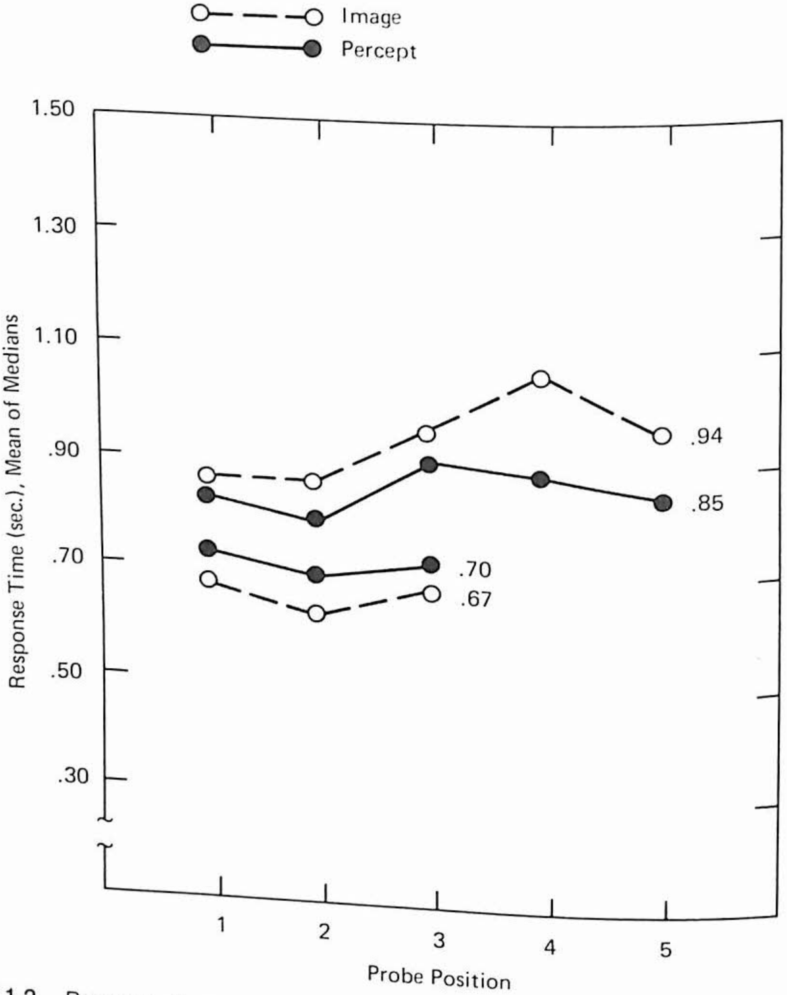

Figure 11-2. Response time as a function of image-percept representation and letter position. (Weber and Harnish. Copyright 1974 by the American Psychological Association. Reprinted by permission.)

Another criterion for determining the maximum size of a simple image using the Weber and Harnish paradigm would be the longest word for which decision times regarding each letter are independent of the number of letters in the word up to that maximum length. This criterion also places an upper bound on the size of a simple image at either three- or four-letter words. However, decisions regarding visual properties of a single letter might be made more rapidly than decisions regarding a single letter from a three-letter word. If this result were obtained, it would suggest that even "simple" images differ in the adequacy of visualization of their component parts.

There are of course other factors, such as the increase in difficulty of processing the serial position probe, that might produce differences as a function of a list length independent of the vividness of the visual image. Perhaps, as Weber and Harnish suggest, the effects can best be assessed by means of a percept control condition, which makes the discrepancy between the image condition and the percept condition the best dependent measure of the change in visual image adequacy with increasing image complexity. However, in the absence of results for one- and two-letter words we do not know that the advantage of the image over the percept might not be substantially greater for one- and two-letter words than for three-letter words. The Weber and Harnish results suggest a maximum size for a simple image, but they do not place a lower bound on its size. It is still possible that even a simple image, consisting of simultaneously activated constituents, shows a progressive decrease in the adequacy of imagery with an increase in the number of constituents.

Weber and Harnish also studied the generation process for the visual image of a word by presenting the probe digit first, followed either by an auditory word to be imaged or by a visual word. As shown in Figure 11-3, the decision time for the visual percept was still reasonably flat as a function of serial position for both three- and five-letter words, but the time to make a decision regarding the letters of the image (generated by the subject from the auditory word) tended to increase from left to right, although there was a significant reversal between the fourth and fifth position for five-letter words. Thus, generation of the visual image (from an auditory word) for both three- and five-letter words is not a simultaneous process, regardless of whether the components of the image for three-letter words can be simultaneously maintained at equal vividness. Furthermore, the process of generating a visual image for a word does not appear to be a strictly left-to-right process. We appear to have some flexibility in the order with which the image components are generated, although the Weber and Harnish results suggest a fairly strong left-to-right component in generating images of words. It is as if the verbal modality were playing a dominant role in the generation of the visual image for words.

Incidentally, Weber and Castleman, using a completely subjective procedure, assessed the maximum rate at which subjects can generate images of successive letters of the alphabet and compared this to the rate at which they can verbally rehearse successive letters of the alphabet. Verbal rehearsal (speech "imagery") was faster (about six letters per second) than visual imagery (about two letters per second).[36] You can perform this experiment for yourself. First, time yourself reciting the alphabet verbally, then time yourself while you go through the alphabet again, this time imaging each

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[36] R. J. Weber and J. Castleman, "The Time It Takes to Imagine." *Perception and Psychophysics,* 1970 (8), 165-68.

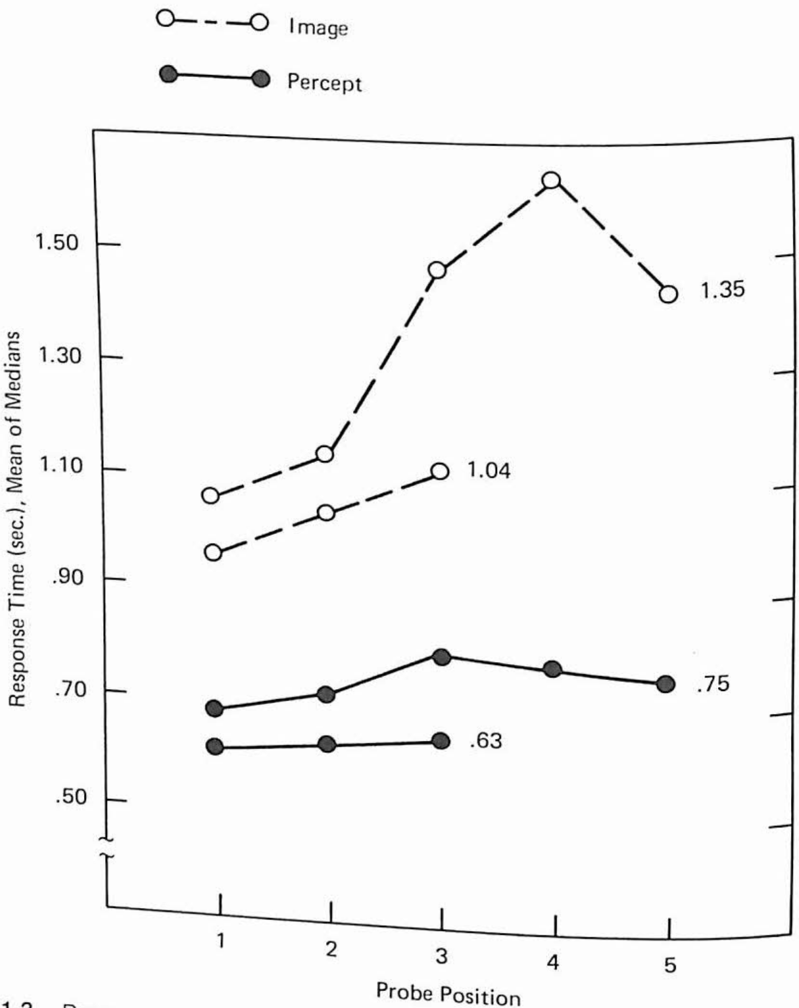

Figure 11-3. Response time as a function of image-percept representation and letter position. (Weber and Harnish. Copyright 1974 by the American Psychological Association. Reprinted by permission.)

letter as if it were projected on a screen. The time to construct the image of each letter mentally should be much longer than the time required for verbal rehearsal of each letter—about three times as long on the average.

In studying the role of attentional focus in retrieving information from images, Kosslyn asked subjects to verify whether a particular previously memorized drawing of an object (car, speed boat, plane, rattlesnake, locomotive) contained some property such as a headlight. In one condition subjects were given the name of the drawing and asked to generate a visual image and to focus on the whole image. In another condition they were asked to focus on one end of the image. Kosslyn demonstrated that the time to make a decision regarding a property was faster in the part condition than in the whole condition for properties within the attentional focus. However, decision time was slower in the part condition than in the whole condition for properties far away from the attentional focus.[37] The drawings used by Kosslyn were moderately complex, suggesting that they might well be beyond the capacity of a simple image (if indeed there is any such thing as a simple image).

Image Size

Kosslyn also investigated the relationship between image complexity and image adequacy, Basically he was concerned with investigating the effects of image size on the speed of verifying the properties of the image. For example, he demonstrated in a number of contexts that the larger the size of the image, the faster properties were verified.

(1) He showed that the smaller characteristics of an imaged animal took longer to verify than larger characteristics. When a subject was instructed to image a cat, it took longer for him or her to verify that the cat had claws than that the cat had a head. In a control condition where subjects were not asked to form a visual image and were presumably performing on the basis of verbal memory, the decision regarding whether a cat had claws was faster than that regarding whether a cat had a head. The difference in verbal memory is presumably because of the stronger association between cat and claws than between cat and head. That this relationship was reversed in the imagery condition verifies that subjects were indeed using visual images to make decisions under the imagery condition. (2) The time for subjects to make decisions about the visual properties of an animal was shorter for large animals than for small animals. (3) When the same animal was imaged at larger and larger sizes, the time to make a decision about some property become progressively shorter.

Kosslyn also demonstrated the limited capacity of imagery by showing that when subjects were required to image an animal next to a matrix of numbers, animal properties were evaluated faster next to a simple (four-cell) matrix than next to a more complex (sixteen-cell) matrix. Furthermore, even when the number of cells in the matrix was held constant, properties of animals imaged next to a physically large four-cell matrix were verified more slowly than properties of animals imaged next to a small four-cell matrix.[38] It appears that the larger the size of the matrix, the more capacity in image memory is consumed in representing it.

As Kosslyn suggests, there may be something analogous to the grain of representation of the visual image—that larger images have a richer grain of representation and are therefore easier to "see," much as a photographic blow-up of a small section makes that section easier to see despite the fact that no information can be added by the enlarging process.

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[37] S. M. Kosslyn, "Scanning Visual Images: Some Structural Implications." *Perception and Psychophysics,* 1973 (14), 90-94.

[38] S. M. Kosslyn, "Information Representation in Visual Images." *Cognitive Psychology,* 1975 (7), 341-70.

Alternatively, effects of size may be subsumed under the effects of image complexity discussed in the previous section. That is, when subjects image a larger object, they may represent it in greater detail, which leads to faster verification of its component properties. Furthermore, to the extent that one image in the field is represented in greater detail, there is less capacity to represent other images, making the verification of their visual properties more time consuming.

Eidetic Imagery

Most of us have friends who claim to be able to remember great quantities of material by forming an image of the words or diagrams on a page. There has been little definitive research on individual variations in image capability, but it seems very likely that the differences are as large as differences in any other human capacity. At one extreme are individuals whose visual capacities are so remarkable that their imagery has been called *eidetic*. (Although such imagery has a special name, there is no reason to believe that eidetikers—subjects said to have eidetic imagery—possess a qualitatively different capacity for visual imagery than the rest of us. Rather, it seems most parsimonious to assume that they represent the tail-end of a distribution in imagery capacity possessed by all of us.)

Eidetikers build their visual images by eye movement scanning of complex pictures, just as the rest of us do. Thus, eidetic imagery is like ordinary visual imagery and unlike sensory afterimages, which would be blurred by eye movements. Eidetikers apparently retrieve visual images by a generative process involving scanning as well.[39]

The eidetikers reported throughout history have ranged from idiot savants to people with normal general intelligence to people of very high general intelligence, so there is no reason to associate eidetic imagery with idiocy or lack of ability to do abstract thinking. Nor is there any reason to believe that eidetic imagery conveys any special intellectual advantage. The most useful memory is associative, and the ability to generate images of all of the pages of hundreds of books, as the "Shass Pollacks" are alleged to be able to do, is of small conceptual value.

IMAGE OPERATIONS

The image modality does not consist of a passive collection of images arranged like so many paintings on a wall or books on a shelf. An equally important component of the image modality is the range of operations that can be performed on images. These operations appear to fall into two basic categories: destructive and nondestructive. Nondestructive operations (already discussed to a considerable extent) include the initial generation or subsequent scanning of one or more constituents of a complex image and zooming (focusing on some part of the image), which may be nothing more than the addition of constituents representing that part in more detail. Scanning operations can be further distinguished on the basis of whether one scans to the front or back, left or right, top or bottom, or any diagonal combination of these six basic directions. Zooming operations can also be subdivided according to whether one zooms at the center, the lower left corner, the upper right corner, etc.

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[39] R. N. Haber and R. B. Haber, "Eidetic Imagery: I. Frequency." *Perceptual and Motor Skills,* 1964 (19), 131-38.

Scanning and zooming should logically be nondestructive, since one is merely adding to the image without negating the simultaneous existence of the rest of the image. Presumably, when an image component is not currently the focus of attention, its vividness decays passively and must be periodically refreshed via the scanning or zooming operations. According to this hypothesis, the more complex the image, the greater the delay between returning to refresh any image component. Successive regeneration of each component would occur in much the same way that an image on a TV picture tube or oscilloscope is generated by an electron gun scanning over all the points on the screen. At present there is little direct evidence to support this hypothesis, and nothing is known concerning the speed of scanning and zooming operations or the activation-decay function for image components.

Destructive operations include deletion, rotation, reflection, translation, magnification, minification, squashing, stretching, and tearing of visual images. The destructive operations that can be performed on images probably include all of the destructive actions that an individual can take on objects in the physical world, as well as some that can only be imagined, but the only destructive operation that has been extensively investigated is mental rotation.

Image Rotation

The first study of image rotation, by Shepard and Metzler, was a kind of spatial relations test in which subjects were to judge whether pairs of projections of three-dimensional shapes were identical or different (Figure 11-4). The pairs were constructed to be mirror-image reflections so as to prevent the subjects from solving the problems by a feature extraction process, without image rotation.

Strong evidence was obtained to support the hypothesis that subjects actually solved these problems by mentally rotating one shape into the other in order to determine congruence. The basic datum supporting this

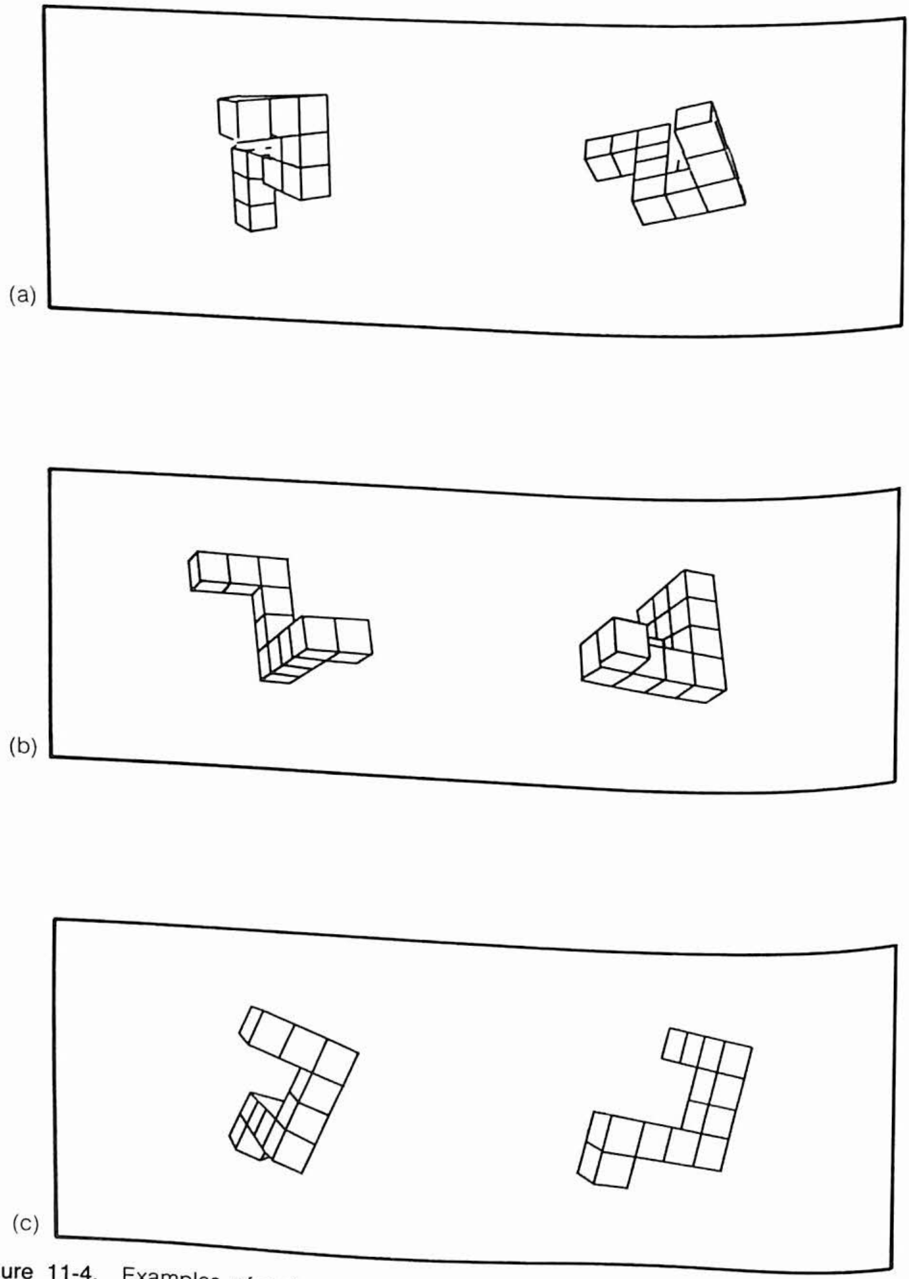

Figure 11-4. Examples of pairs of perspective line drawings presented to subjects by Shepard and Metzler. (a) A "same" pair, which differs by an 80° rotation in the picture plane; (b) a "same" pair, which differs by an 80° rotation in depth; and (c) a "different" pair, which cannot be brought into congruence by *any* rotation. (From Shepard and Metzler by permission. Copyright 1971 by the American Association for the Advancement of Science.)

hypothesis was that the time to reach a "same" judgment increased linearly with the size of the angle through which one object had to be rotated in order to make it congruent to the other. This was true both for rotations within the frontal (picture) plane, as in (a) of Figure 11-4, and for rotations in depth, as in (b). The average reaction times of "same" pairs for rotations in both the picture plane and the depth plane are shown in Figure 11-5.

The Shepard and Metzler study not only demonstrated the existence of the image rotation operation, it also determined a number of important characteristics of this process. First, rotation in the two-dimensional picture plane was not significantly faster for three-dimensional images than rotations in three dimensions (in depth). Thus, there is probably at least some sense in which mental rotation of a solid-object image is three dimensional rather than an operation applied to the two-dimensional projection of the object.

Mental rotation also appears to involve transitions through intermediate stages, rather than being a single jump from one position to another differing by X degrees. Mental rotation of an object image through 60 degrees may consist of three elementary rotations of 20 degrees each. By this hypothesis, we may have learned associations for how a set of spatial features are transformed to a new set of spatial features for a 20-degree rotation in a particular direction. To accomplish a 60-degree rotation, one performs a succession of three 20-degree rotations in the same direction. In a manner not yet understood, the two views of an object determine the direction of rotation, and then the subject proceeds to carry out rotation in that direction over a series of steps. Thus there is a linear (straight line) increase in the time to complete the rotation with an increasing angular disparity, as shown in Figure 11-5.[40]

Cooper and Shepard studied rotation of two-dimensional letter images. The speed of image rotation of these forms was considerably faster than the speed of rotation for the three-dimensional objects studied by Shepard and Metzler. Since Shepard and Metzler had already demonstrated that rotation of three-dimensional objects in the picture plane is not intrinsically faster than rotation in depth, the essential difference appears to be whether the image being rotated is itself two or three dimensional. Cooper and Shepard's task was for subjects to decide whether an original upright letter matched a test character presented at some rotated position, as shown in Figure 11-6. Nonmatching test characters were mirror-image versions of the original letter. After presentation of the original letter, subjects were shown an orientation arrow indicating the angle at which the test character

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[40] R. N. Shepard and J. Metzler, "Mental Rotation of Three-Dimensional Objects." *Science*, 1971 (171), 701-3.

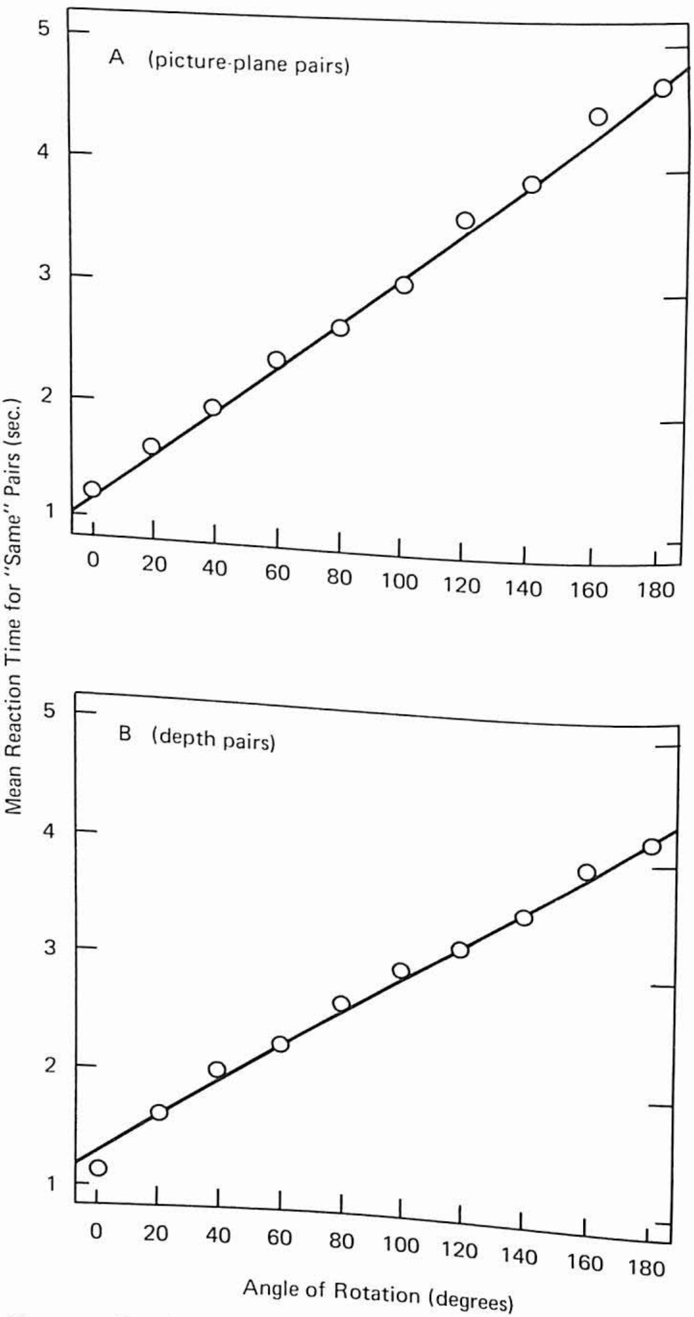

Figure 11-5. Mean reaction times to two perspective line drawings portraying objects of the same three-dimensional shape. Times are plotted as a function of angular difference in portrayed orientation: (a) for pairs differing by a rotation in the picture plane only; and (b) for pairs differing by a rotation in depth. (From Shepard and Metzler by permission. Copyright 1971 by the American Association for the Advancement of Science.)

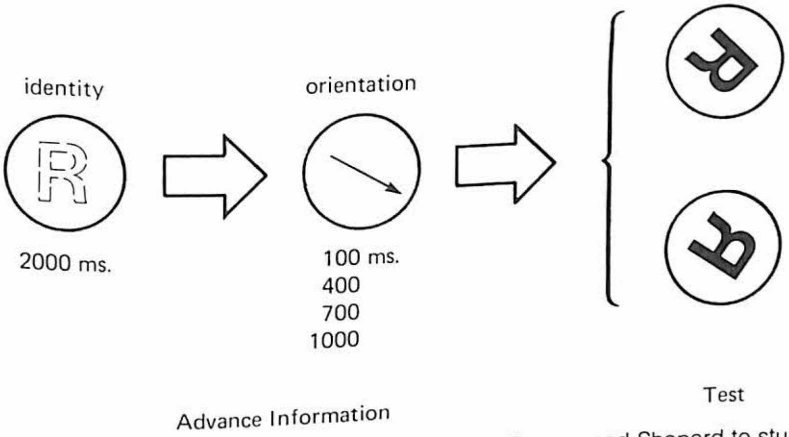

Figure 11-6. The sequence of visual displays used by Cooper and Shepard to study mental rotation of letter images (reprinted by permission).

would be presented following a variable delay from 0.1 to one second, during which they were to rotate the original letter mentally into the test position. When subjects had enough time to rotate the letter to the test orientation, they were able to decide more rapidly whether the original and test characters matched. The speed of mental rotation could therefore be determined.[41]

A subsequent experiment by Cooper and Shepard using a modification of this paradigm also suggested that mental rotation involves a passage of the image through intermediate angular orientations. Subjects were given a test character and instructed to begin mentally rotating it in the clockwise direction at a rate of 60 degrees per half second, paced by an auditory cue of the form: "up," "tip," "tip," "down," "tip," "tip," representing six positions around the face of a clock. When the test stimulus was presented at the orientation coincident with the angle at which the subject was currently imaging the original character, the matching decision was made much more rapidly than when the test character appeared at one of the other five orientations.[42]

Furthermore, Cooper and Shepard imply that when the test character was presented at the position 60 degrees prior to the currently imaged position, it was not processed any faster than a test character presented at a position 60 degrees in advance of the imaged position. This is consistent with the hypothesis that mental rotation is a destructive operation. If rotation were nondestructive, one might expect a more rapid match for a test character presented at a more recently imaged position, 60 degrees prior to the current position, than for a less recently imaged position, 60 degrees subsequent to the current position. According to this hypothesis, the creation of an image in a new position is accompanied by the active destruction or negation of the image at a previous position.

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[41] L. A. Cooper and R. N. Shepard, "The Time Required to Prepare for a Rotated Stimulus." *Memory and Cognition,* 1973 (1) 246-50.

[42] L. A. Cooper and R. N. Shepard, "Chronometric Studies of the Rotation of Mental Images," in W. G. Chase (ed.), *Visual Information Processing.* New York: Academic Press, 1973, pp. 75-176.

The distinction between destructive and nondestructive operations in mental imagery is supported by Coltheart and Glick's case study of a subject with unusual visual imagery capabilities. The subject came to their attention because of her ability to "talk backwards." Talking backwards consists of pronouncing a word or sequence of words in reverse order. For example, given the work *backwards*, she could immediately pronounce it backwards as *sdrawkcab*. Unlike most human beings, this subject can pass the Hebb test for visual imagery of words, in that she can spell a word in reverse direction as rapidly as she can in a forward direction. She apparently does this by generating a visual image of the word and reading the letters from her visual image. She is also extraordinarily good at tachistoscopic recognition of arrays of letters, being able to report about 7.5 letters from an array of eight, while control subjects averaged less than five.

However remarkable these imagery capabilities, the subject is not an eidetiker. Coltheart and Glick concluded that the subject's principal advantage in visual imagery is that the images she generates are extraordinarily resistent to destruction. Thus, she does not appear to be able to form images of large amounts of material or remember such material by means of an image. Rather, text material appears to be remembered in verbal memory with no better than normal capacity. However, what she has in verbal memory can be used to generate a visual image and maintained with very little disruption while she pronounces the material in either direction. Once her images are generated, they are much more stable than those of normal subjects, so she is able to generate and use a much larger visual image and read it off rapidly without interference.

While this resistence to disruption of visual images is beneficial for a nondestructive scanning operation such as spelling a word backwards, it should be deleterious for image processing that uses destructive operations. Indeed, this is the case. The subject is very deficient compared to normal subjects in mental rotation![43]

Reading Transformed Text

It has not been definitely established, but image operations such as mental rotation may play a significant role in the ability to read words that have been transformed in some way, such as rotating each letter 180 degrees, inverting each letter (reflecting the letter about a horizontal axis), reflecting a letter about a vertical axis, etc. Kolers and his colleagues have demonstrated that subjects can read such transformed texts, but less rapidly than normal text.[44] Some transformations are more difficult than others, and ultimately this work should lead to determination of some of the properties of these image operators. While it may appear to be rather unnatural to read texts that have been letter-by-letter reflected or inverted, it is probably a natural occurrence for readers to be oriented at various angles with respect to the text they are reading. Whether such modest angular disparities require a mental rotation operation remains to be determined.

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[43] M. Coltheart and M. J. Glick, "Visual Imagery: A Case Study." *Quarterly Journal of Experimental Psychology*, 1974 (26), 438-53.

Object Concept Recognition

Mental rotation may also be involved in the ordinary object concept recognition process. That is, it is quite conceivable that we have a prototypical concept for a particular object in a particular orientation. Our ability to recognize the object presented in some other orientation might involve mental rotation of the image of that object until it achieves congruence with the prototypical orientation, at which time it can be identified. Massaro, studying the ability to discriminate a circle and an ellipse as a function of slant with respect to the frontal plane, found that the time to make this decision increased with increasing angle of rotation from the frontal plane, as if the subjects had to rotate the image into the frontal plane to determine whether it was a circle or an ellipse.[45] (Massaro interprets his results in a different framework, but the mental rotation hypothesis appears more attractive to me.)

SUMMARY

1. Memory appears to be distributed through the perceptual, motor, and cognitive modalities of the brain.
2. In most right handers the left hemisphere of the cerebral cortex appears to be specilized for verbal processing and memory, while the right hemisphere is specialized for nonverbal processing and memory for material such as spatial relations, imagery, and music.
3. The highest cognitive modalities are specialized for the type of information represented (language or spatial relations) rather than for sensory or motor modalities (vision, audition, or motor control).

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[44] P. A. Kolers, "The Recognition of Geometrically Transformed Text." *Perception and Psychophysics,* 1968 (3), 57-64. P. A. Kolers and D. N. Perkins, "Orientation of Letters and Errors in Their Recognition." *Perception and Psychophysics,* 1969 (5), 265-69.

[45] D. W. Massaro, "The Perception of Rotated Shapes: A Process Analysis of Shape Constancy." *Perception and Psychophysics,* 1973 (13), 413-22.

4. There is an image modality (representing the form of objects—the *what* system) and a spatial modality (representing the location of objects—the *where* system). Both modalities have operations that convert (relate) one form or location to another.
5. One abstract (cognitive) spatial modality represents locations and movements (operations) for all sensory-input and motor-output modalities.
6. Movement concepts in the spatial modality are most closely linked to central motor commands, while position concepts are most closely linked to sensory (visual, auditory, tactile, kinesthetic, etc.) input.
7. The associations from sensory input modalities and motor output to the spatial modality can be modified to adapt to homogeneous and split-field lateral displacement, rotation (tilt), up-down inversion, right-left reversal, magnification, and minification of the visual field. What changes first is often the felt position of parts of the body (a change in the associations between the spatial modality and the tactile, kinesthetic, and motor modalities), but eventually there is a change in the visual-spatial mapping from retinal and eyeball locations onto the spatial modality.
8. Active self-produced movement facilitates both sensory-motor development and adaptation to sensory rearrangement, with a high degree of temporal contiguity required between a movement and the visual feedback from it.
9. An image has a constituent structure just like a verbal proposition. A whole image is analyzed into part images in a manner that can vary with context.
10. Simple images are images whose activation can be maintained as a whole simultaneously, without scanning. Complex images can only be maintained by successive scanning of simple image constituents. Some (more complex) simple images may require successive scanning for generation but not for maintenance.
11. Larger images are clearer or more adequate in a way that improves information retrieval from them. Simultaneous imagery capacity is limited, so the more detailed the representation of one part of an image the less detailed the representation of other parts.
12. There are associations from the verbal modality to the image modality so that, for example, we can visualize the letters of the alphabet or the letters in a word. The generation of images for letters of the alphabet appears to be strictly one letter at a time, with some involvement of the phonetic level of the verbal modality (in pronouncing the letters). The generation of images for the letters in a word may not be limited to one letter at a time, does not always proceed in strict left-to-right order, and does not appear to require pronunciation of the word.

13. Eidetic imagery appears to be qualitatively similar to ordinary visual imagery and unlike afterimages, in that complex eidetic images are acquired by eye movement—scanning—which would blur an afterimage. Retrieval of eidetic images also appears to involve scanning.
14. Scanning (including initial generation of an image) and zooming are logically nondestructive image operations, though there is little evidence to support the notion that they are nondestructive in the human mind.
15. Deletion, rotation, reflection, translation, magnification, minification, squashing, stretching, and tearing are logically at least partly destructive operations, and there is some psychological evidence supporting the destructive character of mental image rotation.
16. Mental image rotation through large angles appears to be accomplished in small-angle steps, leading to a linear increase in time to rotate an image with increasing the size of the angle.
17. Image rotation of two-dimensional forms is faster than image rotation of three-dimensional objects.
18. Mental image rotation may play an important role in recognizing words and nonverbal shapes at different angles of rotation.

12 The Dynamics of Memory

OBJECTIVES

1. To define the concept of memory dynamics for each of the three principal phases of the memory process: acquisition, storage, and retrieval.
2. To discuss whether memory traces are all-or-none or have gradations of strength.
3. To discuss whether there are one or two different types of associative memory trace: short-term memory and long-term memory.
4. To distinguish coding differences and dynamic differences from memory traces.
5. To describe two types of memory disorders: (1) acquisition amnesia, which may result from a loss of chunking capacity, and (2) auditory memory span deficit, which appears to be a defect in the encoding into memory of auditorily presented material.
6. To discuss whether forgetting rates fall into two classes, fast (for short-term memory) and slow (for long-term memory), or are continuously variable, fastest at short retention intervals and progressively slower the older the memory.

The preceding four chapters were concerned with the qualitative coding properties of human learning and memory. The next four are concerned primarily with the quantitative, dynamic properties of learning and memory, such as how rapidly we learn and forget and how rapidly we can retrieve and use previously learned information. Chapters 13, 14, and 15 are devoted to the three temporally distinct phases of the memory process: acquisition (learning), storage (consolidation and forgetting), and retrieval (recall and recognition). The principal variables that affect the time course of acquisition, storage, and retrieval will be discussed along with such basic questions as: What are the stages of learning? How do the conditions of learning affect the rate of forgetting? Is there a consolidation process?

What are the causes of forgetting? Is memory retrieval a direct-access process, or does it involve successive scanning (serial search)?

The present chapter has three major sections. First, we examine the issue of whether memory traces are all-or-none or continuously variable in strength. Second, we take an overview of memory dynamics within the continuous strength formulation for each of the three phases: acquisition, storage, and retrieval. Third, we consider whether there is reason to distinguish two dynamically different types of associative memory traces: short-term and long-term memory. We conclude that there is not. In this third section, some important memory disorders are discussed.

ALL-OR-NONE VERSUS INCREMENTAL MEMORY

Theories of the memory trace can be divided into two classes: discrete (finite-state) theories and continuous (incremental) strength theories.[1] Within the finite-state class, the most extreme form is the all-or-none theory, in which a memory is either present or absent. Within the all-or-none (two-state) theory, memory traces that are present have the value 1 and those that are absent (either because they were never learned or because they have been forgotten) have the value 0. There are no gradations of memory strength in an all-or-none theory, and learning is represented by the transition of the memory traces from the value 0 to the value 1, while forgetting is the reverse transition.

Although responses on recall and recognition tasks are typically either correct or incorrect, most people feel that they have different degrees of confidence in their responses corresponding to different underlying strengths of the memory trace. Thus, there is some intuitive support for each theory. It is difficult to refute either theory on the basis of experimental data.

Both learning and forgetting typically show a progression through many levels of probability of correct performance. As the retention interval increases, the probability of correct response gradually decreases, rather than going suddenly from perfect performance to chance performance at some point in time. However, the all-or-none theory can account for gradual forgetting by assuming that there is some probability of forgetting at any time following learning. As the retention interval increases there is a progressively greater probability that the memory trace will already have been forgotten. This would produce a gradually declining retention function, even for an underlying all-or-none forgetting process. Similarly, gradual increases in correct response probability over successive learning trials for a set of items could be the result of all-or-none learning occurring on different trials for different items within a set.

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[1] For a review of finite-state and incremental models of learning and memory see W. Kintsch, *Learning, Memory, and Conceptual Processes.* New York: Wiley, 1970, pp. 61-85. W. K. Estes, "Learning Theory and the New 'Mental Chemistry'." *Psychological Review,* 1960 (67), 207-23. F. Restle and J. G. Greeno, *Introduction to Mathematical Psychology.* Reading, Mass.: Addison-Wesley, 1970, p. 54. W. K. Estes, B. L. Hopkins, and E. J. Crothers, "All-or-None Conservation Effects in the Learning and Retention of Paired Associates." *Journal of Experimental Psychology,* 1960 (60), 329-39. G. H. Bower, "Application of a Model to Paired-Associate Learning." *Psychometrika,* 1961 (26), 255-80. L. Postman, "One-Trial Learning," in C. N. Cofer and B. S. Musgrave (eds.), *Verbal Behavior and Learning: Problems and Processes.* New York: McGraw-Hill, 1963, p. 60. J. T. E. Richardson, "Verbal Learning: Incremental vs. All-or-None Theory." *Quarterly Journal of Experimental Psychology,* 1970 (22), 196-204.

There are a number of phenomena that are rather awkward to account for in an all-or-none theory. First, when subjects have achieved perfect performance after a number of learning trials, their reaction times for correct responses progressively decrease over subsequent learning trials.[2] In order to account for the correct recall or recognition probability being at 100 percent, it is necessary to assume that the all the relevant memory traces are in the completely learned state. If this is the case, why should there be changes in *any* of the characteristics of the responses such as a decrease in the response latency over subsequent learning trials?

Second, when subjects have made an incorrect response, second guesses are frequently above chance accuracy.[3] This second guess phenomena can be accounted for within an all-or-none theory, but extra assumptions are required, such as assuming that for some reason an incorrect association can pass into the learned state and cause an incorrect response, even though the correct association is also in the learned state. When the subject is told that the response is incorrect, he or she can then sometimes choose the correct response because the correct association is also in the learned state.

There are other, more complex arguments against all-or-none learning theories, but a dedicated all-or-none learning theorist can usually find a way to retain an essential element of the all-or-none theory. If one takes the discrete approach one step further and allows memory traces to be in three states—for example, unlearned, in short-term memory, and in long-term memory—then it becomes even more difficult to decide between the finite-state framework and the continuous strength framework. Finally, one can assume that an item or association has many attributes, each of which is learned and forgotten in an all-or-none manner.[4]

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[2] R. Millward, "Latency in a Modified Paired-Associate Learning Experiment." *Journal of Verbal Learning and Verbal Behavior*, 1964 (3), 309-16. L. Peterson, "Paired-Associate Latencies after the Last Error." *Psychonomic Science*, 1965 (2), 167-68. J. Theios, "Prediction of Paired-Associate Latencies after the Last Error by an All-or-None Learning Model." *Psychonomic Science*, 1965 (3), 311-12. P. Suppes, G. Groen, and M. Schlag-Rey, "A Model for Response Latency in Paired-Associate Learning." *Journal of Mathematical Psychology*, 1966 (3), 99-128. N. C. Waugh and E. C. Holstein, "Recall Latencies of Highly Overlearned Items." *Psychonomic Science*, 1968 (11), 143.

[3] J. R. Binford and C. Gettys, "Nonstationarity in Paired-Associate Learning as Indicated by a Second-Guess Procedure." *Journal of Mathematical Psychology*, 1965 (2), 190-95. A. S. Bregman and D. W. Chambers, "All-or-None Learning of Attributes." *Journal of Experimental Psychology*, 1966 (71), 785-93.

STRENGTH THEORY

Despite the difficulty of definitely rejecting all finite-state formulations of the memory process, there are theoretical advantages to adopting the continuous strength theory, most of which have to do with memory dynamics. Memory will be considered to vary continuously on a dimension called strength. Prior to acquisition, memory traces are considered to have zero strength, but during acquisition (learning), strength increases as a function of study time or the number of study trials, probably to some maximum limit (asymptote). During the retention interval, memory strength will decline as a result of decay and interference. At the time of retrieval, the strength of relevant memory traces remaining at that time determines the probability of correct recall or recognition. (See Figure 12-1.) Higher strength produces a higher probability of correct recognition or recall. Although memory retrieval can take place in about a second, the retrieval of trace strength does appear to be gradual over this time period, as discussed in Chapter 15. The present discussion of memory dynamics will largely make use of the continuous strength formulation, but most of the conclusions regarding memory have equivalent analogues within the finite-state formulation.

A continuous strength theory of memory dynamics does not imply that there are no relatively rapid or abrupt changes in strength during the memory process. We shall discuss some traumatic events during storage that sometimes temporarily and sometimes permanently reduce the effective retrieval strength of a memory trace to zero. When a subject understands material or thinks of some clever visual image or verbal mnemonic for remembering an association during acquisition, the effective strength of the memory trace increases rather abruptly. Such insights concerning effective ways to code the material can occur at various times during the acquisition process in a manner that lends a substantial all-or-none aspect to learning, even within a continuous strength theory. One of the theoretical advantages of the continuous strength formulation is that it permits any

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[4] W. K. Estes, "Toward a Statistical Theory of Learning." *Psychological Review*, 1950 (57), 94-107. G. H. Bower, "A Multicomponent Theory of the Memory Trace," in K. W. Spence and J. T. Spence (eds.), *The Psychology of Learning and Motivation: Advances in Research and Theory*, Vol. 1. New York: Academic Press, 1967, pp. 299-325. See discussion of Estes's stimulus sampling theory in W. Kintsch, *Learning, Memory, and Conceptual Processes*. New York: Wiley, 1970, pp. 94-135.

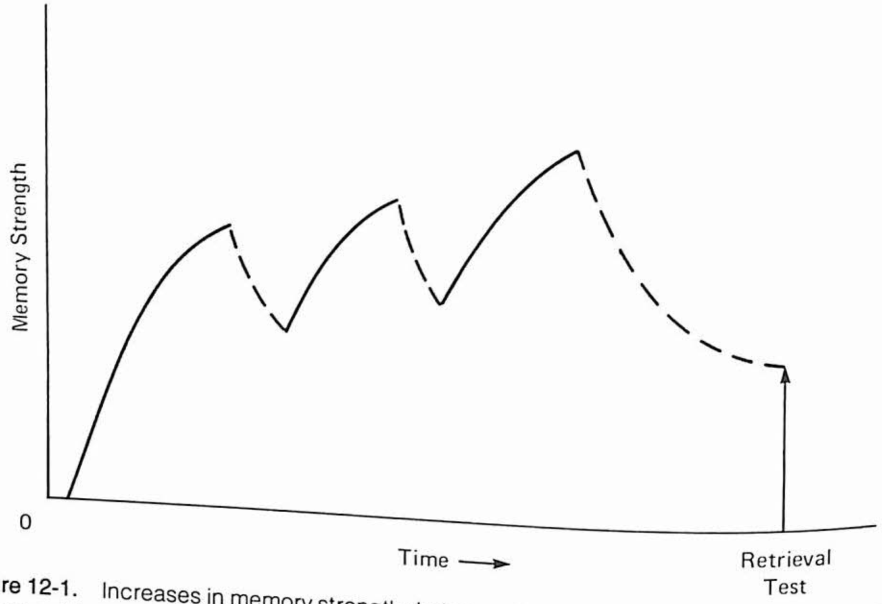

Figure 12-1. Increases in memory strength during each of three learning trials (solid lines) with forgetting (dashed lines) during retention intervals following learning trials. The strength of the memory trace at the time of the retrieval test determines the probability of correct recall or recognition.

degree of all-or-none learning at the same time as it is compatible with gradual changes in the memory trace.

Throughout these chapters on dynamics we shall be discussing changes in memory strength as if strength were directly measurable, but it is not. All one can directly measure are response probabilities. However, statistical decision theory and its application to psychology via signal detection theory provide us with a plausible way of converting response probabilities into measurements of the underlying strength of some psychological variable such as the memory trace.[5] It is by no means clearly established that the memory strength measures obtained in this way are ideal, but this measurement technique is the best one now available. A systematic presentation of statistical decision theory and its application to strength measurement is beyond our scope here, but a brief discussion is presented in Chapter 15. For these chapters on memory dynamics, just assume that theories of acquisition, storage, and retrieval dynamics can be evaluated by direct measurement of memory trace strength. Most of the qualitative conclusions concerning memory are probably not affected by the specific assumptions of the strength measurement process.

[5] W. P. Tanner, Jr., and J. A. Swets, "A Decision-Making Theory of Visual Detection." *Psychological Review,* 1954 (61), 401-9. D. M. Green and J. A. Swets, *Signal Detection Theory and Psychophysics.* New York: Wiley, 1966.

ARE THERE TWO DYNAMICALLY DIFFERENT MEMORY TRACES?

You look up a number in the telephone directory, dial it, get a busy signal, and hang up. Five minutes later you want to dial the number again, but because you have forgotten it you must look it up again. This is short-term memory, so called because it lasts for only a short time. Memory of a briefly presented seven-digit number will last only a few seconds or tens of seconds if you do not rehearse and instead engage in processing unrelated verbal material during the retention interval. By contrast, you can remember your own telephone number or other well-learned list over retention intervals of days, weeks, months, and even years. Much of our long-term verbal memory is of a more meaningful semantic character, but it is clear that even rote verbal material such as familiar telephone numbers can be retained for very long periods. Differences such as this have led some memory theorists to postulate two distinct types of memory traces: short term and long term. Is there any basis for this distinction?

For a time it was thought that verbal short-term memory was a nonassociative buffer store that made it structurally different from associative long-term memory. However we saw in Chapter 8 that at least one component of verbal short-term memory is associative. Throughout these last three chapters we shall only be concerned with the dynamics of associative memory and not nonassociative iconic or echoic memory.

It also used to be thought that verbal short-term memory was encoded at the phonetic level of the verbal modality, while verbal long-term memory was encoded at the semantic level. However, since we know how to read, spell, recognize, and pronounce words, we know there is also long-term graphic and phonetic memory. At the same time, short-term semantic memory traces are undoubtedly formed during the processing of sentences. Such considerations negate the simple equation of short-term memory with lower structural levels and long-term memory with higher semantic levels. It is still logically possible that there are two separate, dynamically different types of traces—short term and long term—existing at one or both levels of the verbal modality, but as we shall see, there is no evidence at present to compel such a conclusion.

Since research on short-term memory became popular in the middle 1950s, hundreds of studies have been interpreted to support a distinction between short-term and long-term memory, but it is now clear that all the evidence alleged to support this distinction is equally compatible with a single-trace theory.[6] There are different reasons that various pieces of evidence for the distinction between short-term and long-term memory are inconclusive, but two recurrent conceptual errors underlie most of the faulty reasoning: (1) encoding confounding and (2) superficial comparisons of forgetting rates.

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[6] W. A. Wickelgren, "The Long and the Short of Memory." *Psychological Bulletin,* 1973 (80), 425-38. W. A. Wickelgren, "More on the Long and Short of Memory," in Deutsch and Deutsch, *Short-Term Memory,* pp. 65-72.

ENCODING CONFOUNDING

The association between *cat* and *mouse* is different from the association between *salt* and *pepper*. This does not mean that there is anything logically different about the linkage between cat and mouse as opposed to the linkage between salt and pepper (though there might be). However, because the concept pairs are different, one must assume that there are physically different (though possibly equivalent) connections between them. Since the associations are physically different, it is possible to find some manipulation that will affect the two traces differently. For example, one might force the subject to say "salt-water" over and over again hundreds of times and demonstrate that this produced some interfering effect on the probability or latency with which she or he would respond with "pepper" on a word association test given "salt" as the stimulus word. Such a manipulation would have much less of an effect or no effect at all on the probability or latency of the subject's responding with "mouse" on a word association test to "cat" as the stimulus.

Stated more abstractly, if a subject has learned two word-word paired associates, represented as *AB* and *CD*, interpolated learning of *AE* will cause more interference with the retention of the *AB* association than with the retention of the *CD* association. The fact that a particular manipulation affects two traces differently does not establish that the two traces are dynamically different. That is to say, the laws of forgetting are not necessarily different for two memory traces simply because some manipulation affects them differently. In the case of experimentally or extraexperimentally (outside the lab) learned word-word paired associates, we would generally want to consider that the pairs are stored in the same modality, and that they have the same dynamic laws of forgetting.

What about a less obvious case, where memory for an abstract sentence is compared to memory for a complex picture? Here one might produce evidence to support the assumption of two traces stored in different modalities by showing that conditions presumed to affect the verbal modality had an effect on the verbal memory trace but not the image trace, and vice versa. (There are obviously some substantial difficulties in establishing that the two traces are in different modalities, but these are irrelevant to the present discussion.) However, any demonstration of a modality difference proves nothing about whether the two traces are dynamically different. Memory traces of different modalities might well have completely equivalent physiological mechanisms and follow precisely the same psychological laws of forgetting, which is just what we assume to be the case for two traces that are different traces in the same modality. To demonstrate that two traces are dynamically different, it must be shown that any alleged difference in forgetting properties can be explained by assuming a dynamic difference rather than just a difference in coding properties such as modality or level of encoding.

There are many examples of failure to be aware of the possibility of encoding differences in the attempt to marshall evidence in support of a simple dichotomy based on trace longevity, but perhaps the most interesting examples of this confounding have come in the study of patients with memory disorders. We shall consider two classes of patients: those with *acquisition amnesia*, who were considered to have relatively intact short-term memory but grossly impaired long-term memory, and those with a *memory span deficit*, who were considered to have intact long-term memory but impaired short-term memory. Patients with such disorders were once considered as evidence of a dichotomy between short-term and long-term memory traces, but we now know that this interpretation is the consequence of a serious encoding confounding.

Acquisition Amnesia

There are people who appear to be fixed at a certain age in life as far as their memories are concerned (their bodies do age, so aging is not all in the mind). A 45-year-old man can remember his life experiences up to age 28 but he cannot remember anything that had happened to him since that time. At age 28 an injury occurred in the hippocampus and mesial temporal area of the cortex that appears to play a vital role in establishing new memories, and since then the experiences of life have not been permanently registered in memory. Some people are like this because of neurosurgical operations that removed brain tissue in the mesial temporal cortex and hippocampus for the relief of epilepsy. (These operations are no longer performed.) Other people have lost this ability to establish new long-term memory traces because of accidents, still others as a result of Korsakoff psychosis, a disorder that can result from prolonged alcoholism. Some elderly individuals exhibit this same acquisition amnesic deficit. They can remember events of their younger days, but they have trouble learning new things.[7]

[7] W. B. Scoville and B. Milner, "Loss of Recent Memory after Bilateral Hippocampal Lesions." *Journal of Neurology, Neurosurgery, and Psychiatry*, 1957 (20), 11-21. B. Milner, "Amnesia Following Operation on the Temporal Lobes," in C. W. M. Whitty and O. L. Zangwill (eds.), *Amnesia*. London: Butterworths, 1966, pp. 109-33. B. Milner, S. Corkin, and H. L. Teuber, "Further Analysis of the Hippocampal Amnesic Syndrome: 14-Year Follow-Up Study of H. M. *Neuropsychologica*, 1968 (6), 215-34. H. L. Teuber and B. Milner, "Persistent Anterograde Amnesia after Stab Wound of the Basal Brain." *Neuropsychologia*, 1968 (6), 267-82. G. A. Talland, *Deranged Memory: A Psychonomic Study of the Amnesic Syndrome*. New York: Academic Press, 1965. V. A. Kral, "Memory Disorders in Old Age and Senility," in G. A. Talland and N. C. Waugh (eds.), *The Pathology of Memory*. New York: Academic Press, 1969, pp. 41-48.

Many patients with serious learning deficits also have a variety of other cognitive disorders, which makes it difficult to draw precise conclusions about memory. However, there are people who exhibit relatively pure deficits in the acquisition of new long-term memory traces without exhibiting any significant lowering of intelligence (as measured by IQ tests) or any serious perceptual or motor deficits. Such people typically show only a modestly reduced immediate memory span. Memory for previously established long-term memories is well preserved, the primary deficiency being in the establishment of new long-term traces. Such people converse fairly normally, making allowances for their inability to remember what has been discussed a few minutes previously.

Once in the course of testing one of these people, I had a rather eerie experience. The patient was a young man in his twenties who had recently suffered brain damage because of an unusual fencing accident. Suzanne Corkin introduced me to the patient saying something like, "This is Wayne Wickelgren." The young man replied "Wickelgren, that's a German name isn't it?" I said, "no." Then he said, "Irish?" Again I said, "no." Then he said "Scandinavian?" and I answered "yes." I talked with him for perhaps five minutes, and then I had to leave to make a telephone call. When I returned, everyone was standing in approximately the same locations as before. Sue, realizing that the patient would have no knowledge of ever having met me before, reintroduced me to him. After she said, "This is Wayne Wickelgren," he proceeded to say, "That's a German name, isn't it?" I replied, "no." Then he said, "Irish?" I said, "no," and he said, "Scandinavian?"—exactly the same series of questions he had asked the first time he met me. One gets the feeling that such a patient is fixed at a certain time in life and lives every minute with the set of experiences possessed at that time.

This anecdote is somewhat misleading: Most amnesic patients slowly learn new pieces of information, provided the information is particularly salient and frequently repeated. The famous acquisition amnesic patient H. M., investigated by Milner and her colleagues, knows he has a memory problem, and he must have learned this after he acquired the problem. He also knows some significant public events that have occurred since the oneset of his disorder, such as the assassination of John Kennedy. The ability to form new long-term memory traces is not eliminated, but it is enormously reduced.

What has primarily been reduced is H. M.'s ability to acquire new semantic (conceptual and propositional) memory traces. He and other amnesic patients show substantial ability to acquire other types of long-term memory. For example, Corkin demonstrated that H. M. showed nearly normal trial-to-trial improvement in a perceptual-motor learning task of keeping a stylus in contact with a wavy line mounted on a rotating drum. When H. M.

was tested for retention of the perceptual-motor task, he showed as good retention as the control subjects, in terms of the time on target measure of perceptual-motor skill, although he denied ever having participated in such an experiment before![8] Thus, cognitive memory for participating in the experiment appeared to be completely gone, but the perceptual-motor skill was well retained.

A series of studies by Warrington and Weiskrantz on a group of amnesic patients in England has shown that such patients can further strengthen already existing vertical associations between the structural attributes of words and pictures and the concepts (chunk nodes) for which we have names. The test involved presenting a highly fragmented word or picture of a familiar object, such as that shown at the top of Figure 12-2, and then presenting the word or picture in progressively more and more complete form until the subject recognized (named) it. This was done for several different words or pictures, constituting one trial, and then repeated for the same words or pictures on a series of trials. Both normal subjects and amnesic patients improved in their ability to recognize the fragmented versions of previously presented words and pictures as a result of exposure to them on previous trials, even though in some cases an entire day inter-

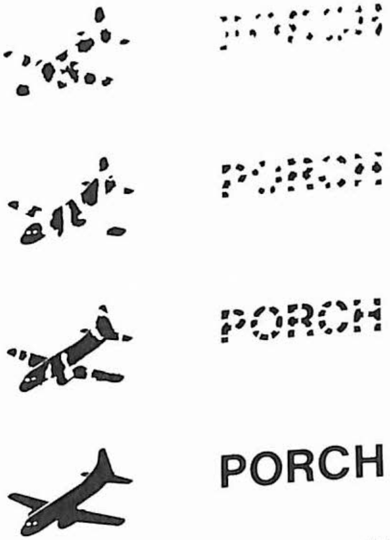

Figure 12-2. Examples of fragmented picture and word. (From Warrington and Weiskrantz by permission.)

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[8] Scoville and Milner, "Loss of Recent Memory." Milner, "Amnesia Following Operation." Milner, Corkin, and Teuber, "Further Analysis." S. Corkin, "Acquisition of Motor Skill after Bilateral Medial Temporal Lobe Excision." *Neuropsychologia*, 1968 (6), 255-65.

vened between trials.[9] Thus it appears that certain kinds of long-term learning are no more seriously impaired in amnesic patients than is immediate memory span.

Warrington and Weiskrantz have also demonstrated that existing associations in semantic memory (for example, category membership associations such as animal-dog) can be primed or strengthened in amnesic patients. In one study amnesics and normal controls were given a list of ten category-example pairs (such as yellow flower-buttercup, shellfish-clam). After a retention interval of one minute they were tested for recall of the example given the category name as cue. Amnesics were impaired compared to controls, but not so drastically as on novel paired-associate learning.[10] The acquisition that amnesics appear to lack is the capacity to form new chunk nodes. The ability to strengthen associations between existing chunks (attributes, concepts, and propositions) in memory may be completely or almost completely unimpaired, but formation of new vertical associations to define chunk nodes is drastically impaired.

This inability to form new chunk nodes should make such amnesic patients extremely subject to retroactive and proactive interference, even in the kinds of learning they can do. Confirming evidence comes from two further experiments by Warrington and Weiskrantz. These experiments showed that amnesic subjects were much more seriously impaired than normal subjects in recall of *C* given *A* in an *AB-AC* proactive interference paradigm involving the priming of previously existing category-member or part-whole associations (*eno-enough* or *eno-enormous*).[11]

Whatever the nature of the memory deficit in these patients, one thing does appear to be established: They have deficits in initial acquisition or retrieval or both, but not in storage. Whether acquisition for some material was modestly or markedly reduced, the subsequent rate of forgetting for these patients has always been comparable to that of normal subjects. This is true for long-term perceptual-motor learning, short-term verbal memory, and long-term verbal memory.[12]

In view of their greater susceptibility to interference, it would not be surprising in certain conditions to find a faster "forgetting" rate in amnesics than in normal controls. There are two necessary conditions: (1) The material must be of the type that normals often learn by forming new chunk nodes, but some learning is possible by further strengthening (priming) existing associations. (2) The retention interval should be filled with highly similar (same stimuli, new responses) interfering learning of associations of the same type as original learning (that is, priming of previously existing associations). Obtaining more rapid forgetting in amnesics under these conditions would be most parsimoniously interpreted as a consequence of the difference in initial encoding in normals and amnesics. It would not be an indication of two dynamically different types of traces, with amnesics being able to form only the short-term ones. As we have seen, acquisition amnesics are able to acquire long-term traces that are forgotten at normal rates under some conditions, so there is no support here for a dichotomy based on trace longevity.

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[9] E. K. Warrington and L. Weiskrantz, "New Method of Testing Long-Term Retention with Special Reference to Amnesic Patients." *Nature*, 1968 (217), 972-74. E. K. Warrington and L. Weiskrantz, "Amnesic Syndrome: Consolidation or Retrieval?" *Nature*, 1970 (228), 628-30.

[10] E. K. Warrington and L. Weiskrantz, "The Effect of Prior Learning on Subsequent Retention in Amnesic Patients." *Neuropsychologia*, 1974 (12), 419-28.

[11] *Ibid*.

[12] Corkin, "Acquisition of Motor Skill." A. D. Baddeley and E. K. Warrington, "Amnesia and the Distinction Between Long- and Short-Term Memory." *Journal of Verbal Learning and Verbal Behavior*, 1970 (9), 176-89. W. A. Wickelgren, "Sparing of Short-Term Memory in an Amnesic Patient: Implications for Strength Theory of Memory." *Neuropsychologia*, 1968 (6), 235-44. W. A. Wickelgren, "Single-Trace Fragility Theory of Memory Dynamics." *Memory and Cognition*, 1974 (2), 775-80.

Auditory Memory Span Deficits

In 1969 Warrington and Shallice reported a patient who first appeared to have precisely the opposite disorder from that of the amnesic. This patient was impaired in verbal memory span, but could quite normally learn lists of paired associates and other materials used to study long-term memory. Other subjects with this type of disorder have also been reported. Warrington and Shallice's patient, K. F., had an auditory digit span of approximately two, which, of course, is phenomenally low for someone able to learn a list of paired associates at close to normal rate. Warrington and Shallice subsequently determined that this was not a general impairment of short-term memory, but an impairment of memory for material presented in the auditory modality. For example, K. F.'s visual short-term memory span was within normal limits.

He has no problem in learning with auditory presentation of single words or word pairs, since this does not exceed his capacity. But when the number of auditorially presented items exceeds two at a time, K. F. is severely impaired. Warrington and Shallice also describe K. F.'s speech as "halting," which suggests that in verbal output he is only able to store a very short string of one or two words or familiar phrases at the phonetic level of the verbal modality.[13]

The verbal short-term memory data and the speech data are consistent with a severe impairment at the phonetic level of the verbal modality. Once this level-modality deficit is acknowledged, there appears to be no evidence of a general impairment of short-term memory as opposed to long-term memory. Here again, the nature of the deficit appears to be specific to a type of encoding and is not relevant to establishing the existence of traces with different dynamics of acquisition, storage, or retrieval.

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[13] E. K. Warrington and T. Shallice, "The Selective Impairment of Auditory Verbal Short-Term Memory." *Brain,* 1969 (92), 885-96. E. K. Warrington and T. Shallice, "Neuropsychological Evidence of Visual Storage in Short-Term Memory Tasks." *Quarterly Journal of Experimental Psychology,* 1972 (24), 30-40.

COMPARISON OF FORGETTING RATES

Many studies of retention have found a period of a few seconds or tens of seconds following learning during which memory undergoes rapid forgetting, followed by a period of relatively slow forgetting. In one form or another, this difference in forgetting rate has often been used to argue for the existence of two memory traces. Gruneberg was the first to point out the fallacy in this argument. If one tracks a memory trace over a longer period of time—not for just the first few seconds or tens of seconds, but for minutes, hours, days, weeks, and years following acquisition—one observes that the rate of forgetting is *continually* decreasing, and that there is no point in this span where one sees an abrupt break, as if one component were dropping out and another taking over. Rather, what one sees is a smoothly decreasing level of trace strength, with a rate of loss that is continually decreasing the older the memory. The initial period of rapid forgetting is merely what one would expect from a simple extrapolation of the law that the younger the memory trace the more rapid the rate of forgetting.[14]

Furthermore, even if some situations require the assumption of two memory traces with different forgetting rates, it is quite possible that the two-component memory traces result from coding in two different modalities or two different levels of the same modality, with the same dynamic type of trace mediating each. Depending on the nature of encoding, a trace will be more or less subject to interference from the processing of subsequent material. Traces that are subject to greater amounts of interference will show more rapid forgetting, even if the nature of the trace and its dynamic laws are completely equivalent to that of another, more slowly decaying trace.

Rate of forgetting per se is not germane to the issue of determining the number of dynamically different memory traces. What is necessary is to show that the laws of acquisition, consolidation, decay, interference, or retrieval are different, and this has not been done. It remains most parsimonious to assume a single type of associative memory trace that shows an initially rapid rate of forgetting that progressively slows the older the memory trace. We shall discuss the acquisition dynamics of this associative memory in the next chapter, and its storage and retrieval dynamics in Chapters 14 and 15.

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[14] Wickelgren, "Single-Trace Fragility Theory." M. M. Gruneberg, "A Dichotomous Theory of Memory—Unproved and Unprovable?" *Acta Psychologica*, 1970 (34), 489-96. W. A. Wickelgren, "Trace Resistance and the Decay of Long-Term Memory." *Journal of Mathematical Psychology*, 1972 (9), 418-55.

SUMMARY

1. Coding refers to the qualitative structure of representation in memory. Dynamics refers to quantitative changes over time in acquisition, storage, or retrieval.
2. It is plausible to assume that memory traces have many gradations of strength, although it is possible that such gradations result from all-or-none acquisition and forgetting of each of a large number of component attributes.
3. Acquisition (learning) probably has some gradual increases in strength, but trace strength often increases abruptly when one thinks of an effective way to encode some material into a conceptual unit (image or proposition).
4. So far as we can tell, normal forgetting is always a gradual reduction in strength, though traumatic injuries can cause abrupt amnesia.
5. In recall and recognition, the remaining strengths of the relevant memory traces are retrieved over a period of time on the order of one second for a single act of retrieval.
6. There is reason to distinguish nonassociative traces, such as underlie iconic and possibly echoic memory, from associative traces. There are also numerous coding differences between associative memory traces in different modalities and levels of a modality. However, there is no reason to assume that there is more than one dynamic type of associative memory trace.
7. Acquisition amnesia is a difficulty in new conceptual learning that may result from a loss of chunking capacity.
8. An auditory memory span deficit results a great reduction in the capacity to acquire new memory tracs via auditory sensory input.
9. The forgetting rate for a memory trace appears to get progressively slower the longer the time since learning.

13 Acquisition: Verbal Learning Dynamics

OBJECTIVES

1. To describe the four stages of paired-associate learning as an example of how the learning of even a simple list of pairs is composed of semi-independent parts.
2. To discuss the effects of repetition on degree of learning and subsequent retention.
3. To discuss the enormous facilitation of learning that results from taking items to be associated and incorporating them into a unitary image or verbal propositional chunk.
4. To describe how forgetting rate may be related to the level of processing at the time of acquisition, including a brief discussion of the pros and cons of speed reading.
5. To point out that it is how one processes (encodes) material that is important for learning and not whether one *intends* to learn it.
6. To discuss the beneficial effects of spaced practice for both learning and retention.
7. To describe how prior learning can retard acquisition of subsequent competing associations and cause proactive interference in recall, but not recognition, of the subsequent learned association.
8. To describe the effects of level of arousal on learning and retention and briefly consider whether learning can occur during sleep.

As you study the material in this book there are at least two somewhat distinct parts or stages in your learning. First, you must learn the meanings of the new concepts presented in each section. Second, you must learn the important propositions (the general principles and a few of the specific facts) that are formulated using these concepts. Roughly speaking, you must learn some new words and some new sentences, though it is the meanings of these words and sentences that you must learn, not the sounds or spellings of the words. Learning the definition of a new concept is an example of chunking: forming a new node to stand for a combination of old nodes. As discussed in Chapter 10, learning a new proposition may also be an example of chunking, but at a higher level. We do not yet know much concerning the stages involved in learning complex sentential material, but there have been some rather careful analyses of the stages in paired-associate learning. These stages are discussed in the following section.

THE STAGES OF PAIRED-ASSOCIATE LEARNING

From the experimental and theoretical work of a number of investigators in the field of verbal learning, most notably Benton Underwood, Rudolph Schulz, Leo Postman, Edwin Martin, Eleanor Gibson, and William McGuire, we have a fairly clear indication that paired-associate learning is composed of four somewhat distinct stages: stimulus learning, response learning, response set formation, and pair association.[1] Stimulus and response learnings are examples of chunking at the concept level, while response sets and pair association are probably examples of chunking at the propositional level.

Stimulus learning refers to the development of a stable encoding of the stimulus such that it can be recognized as familiar from one trial to the next and such that the representation of the stimulus is sufficiently distinct (differentiated) from the representation of other stimuli to minimize interference in the acquisition of associations to responses. Perhaps the best evidence for the importance of stimulus recognition in paired-associate learning and its independence from any association to the response items is provided in a study by Martin. Martin used the study-test method. On each trial subjects were exposed to 12 pairs with the stimulus items consisting of consonant trigrams and the responses consisting of the digits 1, 2, and 3. During the test phase of each trial, the 12 stimulus items were mixed with 12 new consonant trigrams and subjects were required to give two responses: a yes-no recognition decision regarding whether the test trigram was old or new and then a choice of one of the three possible response digits. In the 12 study-trials, six of the trigram-digit pairs were consistently paired with the same digits, and six were randomly repaired from trial to trial. Subjects were told about the two types of trigram-digit pairs and were told that their task was to give the digit most recently associated with any trigram stimulus. Martin found that the probability of giving the correct digit response to a trigram was essentially at chance in cases where the subjects did not correctly recognize the trigram, but was considerably above chance when they did. Thus, recognition of the stimulus appears to be a necessary precondition for learning the association to the correct response. However, association to the correct response appeared to play no role in stimulus recognition, since the probability of correctly recognizing an old trigram increased over trials in an identical manner both for the trigrams consistently paired with the same digit responses and for the repaired trigrams. Thus, the development of a stable *S-R* association in this case made no contribution to the stimulus recognition process, but stimulus recognition was critical for the formation of a pair association.[2]

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[1] E. Martin, "Transfer of Verbal Paired Associates." *Psychological Review*, 1965 (72), 327-43. E. J. Gibson, "A Systematic Application of the Concepts of Generalization and Differentiation to Verbal Learning." *Psychological Review*, 1940 (47), 196-229. W. J. McGuire, "A Multipurpose Model for Paired-Associate Learning." *Journal of Experimental Psychology*, 1961 (62), 335-47. B. J. Underwood and R. W. Schulz, *Meaningfulness and Verbal Learning*. Chicago: Lippincott, 1960.

The exact character of the stimulus-learning phase probably varies across different paired-associate learning tasks. In some cases subjects probably achieve stimulus differentiation by integrating the separate components of each stimulus item into a common chunk representative. In the case of nonsense syllables, this may mean associating each nonsense syllable with a familiar word that can serve as a mediator between the stimulus item and the response item to which it is paired. In other cases the subjects appear not to integrate the separate attributes of the stimulus items, but rather to select a component attribute from each stimulus item that distinguishes it from every other item in the list and associate that stimulus component to the response.

Response Learning

The Underwood and Schulz studies indicate the critical importance of the response-learning stage. They and others have demonstrated that the more familiar, meaningful, or pronounceable as a unit the response item is, the faster paired-associate learning occurs.

Familiarity can be measured by the frequency of occurrence in a language for natural verbal units, such as words, letters, or digits. For nonword nonsense syllables or consonant trigrams, familiarity can be measured by such things as the frequency with which the second letter of the nonword follows the first in ordinary English words, added to the frequency with which the third letter follows the second. This is often referred to as the summed diagram frequency of a nonsense syllable or consonant trigram. Meaningfulness has been typically measured by the number of associations the item elicits in some period of time. (Another name for the meaningfulness variable is association value.) Pronounceability is generally determined by means of subject ratings. All three of these variables are highly correlated with each other, and each is positively correlated with the speed of paired-associate learning. Of the three, Underwood and Schulz found that pronounceability was the most important factor.[3]

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[2] E. Martin, "Relation Between Stimulus Recognition and Paired-Associate Learning." *Journal of Experimental Psychology*, 1967 (74), 500-505.

Response Sets

Postman and his colleagues have demonstrated that during paired-associate learning subjects develop a set to produce the correct responses.[4] Such sets can be thought of, using the terminology of McGovern, as associations from contextual or list-name concepts to each of the responses in the list. These associations are logically different from the specific associations of each stimulus item to its response item. As will be discussed in the chapter on storage, the loss of such response sets is one factor that produces forgetting in paired-associate recall. Indeed, when a subject first learns a list of *AB* pairs and then a list of *AC* pairs, one of the important factors in the retroactive interference caused by *AC* learning on the subsequent recall of the *AB* pairs is the development of a set to produce the *C* responses and the suppression of the set to produce the *B* responses.

There is no reason to postulate separate learning and forgetting processes for response sets that are different in kind from the more specific item-to-item associations. However, contextual-to-item associations and item-to-item associations are logically separate and worth distinguishing for a number of purposes. For one thing, the development of response sets can occur before the development of specific associations between the stimulus and response items. One source of evidence supporting this is that when subjects make overt intrusion errors in paired-associate recall, these intrusions are vastly more likely to be other items from the list (intralist intrusions) than items from outside the list (extralist intrusions). Furthermore, subjects have typically learned to differentiate the stimulus and the response sets, since intrusions tend to be predominantly of other response items rather than stimulus items in the list, even when the stimuli and responses are the same type of material (both consonant trigrams or both words, etc.).

Pair Association

To perform correctly in a paired-associate learning test, one needs to do more than learn the stimuli, learn the responses, and develop associations from the context to the set of responses. One must also form specific associations to link each stimulus item with each response item. Naturally the greater the degree of prior association between a stimulus and a response (as measured for example by word-association tests) the greater the speed of paired-associate learning.

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[3] Underwood and Schulz, *Meaningfulness and Verbal Learning*.

[4] See L. Postman and B. J. Underwood, "Critical Issues in Interference Theory." *Memory and Cognition*, 1973 (1), 19-40.

However, a growing number of memory theorists consider that the association of stimuli and responses frequently involves the formation of new chunk representatives that integrate the stimulus and response items of a pair into a common image or verbal proposition (sentence). Without a doubt the most effective variable influencing the speed of verbal learning is the degree to which subjects can employ visual imagery or verbal mnemonics of some kind to integrate the stimulus and response items into a common superordinate unit.

Paivio has demonstrated that subjects' ratings of the capacity of words to evoke concrete visual imagery is an extremely potent predictor of the speed of paired-associate learning.[5] Instructions to integrate the two elements of a pair into a common visual image or to make up a sentence involving both items frequently produces a strong association between the items of the pair in a single trial of no more than five or six seconds.

The verbal-mediator mnemonic of thinking of some concept that is strongly associated to both the stimulus and response items, such as generating the word *bacon* to link the elements of the pair *B-eggs*, can probably be considered within the same framework. A mediator may be effective because it has substituted a chain of two already strong associations for one weak association or because it links both members of the pair via a common superordinate image of bacon and eggs. (Incidentally, in the latter example the association of *B* to bacon might be thought of as the development of a recognition-encoding response to the stimulus, a part of the stimulus-learning phase that enriches the encoding of the stimulus and serves to differentiate it from the other stimuli in the list. The logical distinction between the four phases under some circumstances should not be taken to imply that they are logically distinct under all circumstances.)

DEGREE OF LEARNING

The first law of learning, as confirmed by thousands of learning studies, is that memory improves with practice. The probability of occurrence of a conditioned response increases with an increasing number of conditioning trials pairing *CS* and *US*. The probability of correct recall of a response word to a stimulus word in paired-associate learning increases with an increasing number of learning trials.

Repetition, Retrieval, and Rehearsal

Each trial of a paired-associate learning experiment presents a subject with a stimulus item for a brief period (typically two seconds), during which the subject must anticipate the response item. Following the two-second anticipation interval, there is typically another two-second interval in which the stimulus and response items are presented together. This time can be used by the subject to check the correctness of his or her previous response and to engage in further learning of the pair. After all the pairs have been presented on a given trial, the order of the pairs is rearranged for the next trial. In a typical experiment it might require ten trials to attain a learning criterion, such as one completely correct anticipation of all of the response items in the list. Over the entire ten trials the total time devoted to attempts to recall the response items would be ten trials times two seconds per trial or 20 seconds in all, and the total amount of time spent studying the pairs following recall attempts would also be 20 seconds.

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[5] A. Paivio, *Imagery and Verbal Processes*. New York: Holt, 1971.

One might think that the time spent in active attempts to recall response items would be so occupied with memory retrieval that it would not contribute to the acquisition of memory traces, but this definitely appears not to be the case. A great deal of learning occurs as a result of active attempts at memory retrieval. A study by Gates varied the percentage of time allocated to reading material to be learned as opposed to active attempts to recall that material (with prompting). Learning efficiency was greater the larger the proportion of time spent in active recall up to 80 percent of the total learning time.[6] The advantages of active attempts to recall over reading vary for different types of material and for different stages of learning, but, after the first reading, it appears always to be beneficial for learning to attempt to recall what you have read.[7]

Further acquisition of memory strength can clearly occur as a part of the retrieval process. Many studies showing an increase in trace strength with an increasing opportunity for rehearsal of previously presented material also support this hypothesis, since rehearsal in the absence of appropriate external stimulus information is essentially one type of memory retrieval. Whenever the material to be learned is within the span of immediate memory or for some other reason has a high probability of correct recall, it may make little difference whether the subject has the material physically present to study or generates it via the rehearsal process. Greater degree of learning is achieved with greater study time either way.[8]

Acquisition Dynamics and Mnemonics

If one were to sum the total time spent in learning to a criterion of one correct anticipation of all the response members in a list, one might gain the impression from the typical paired-associate learning experiment that tens of seconds or even minutes were required to learn some of the easiest word pairs, but that would be a gross overestimate of the time required to establish a reasonably high degree of strength for a single association under other conditions. When subjects are given mnemonic instructions to learn paired associates by embedding both members into a common visual image or a sentence, five or six seconds is typically sufficient studying time to produce a memory trace that will last for retention intervals of hours or days following learning.

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[6] A. I. Gates, "Recitation as a Factor in Memorizing." *Archives of Psychology*, 1917 (6), No. 40.

[7] See McGeoch and Irion, *The Psychology of Human Learning*, pp. 507-10.

[8] L. R. Peterson and M. J. Peterson, "Short-Term Retention of Individual Verbal Items." *Journal of Experimental Psychology*, 1959 (58), 193-98. S. Hellyer, "Supplementary Report: Frequency of Stimulus Presentation and Short-Term Decrement in Recall." *Journal of Experimental Psychology*, 1962 (64), 650.

Whether this large difference in acquisition time represents a fundamental difference in the time to form direct associations as opposed to indirect mediated associations or between structural rote learning and meaningful semantic learning is unclear. Subjects frequently report using mnemonic devices of one kind or another in ordinary paired-associate learning experiments despite the absence of instructions to do so. The greater time required to learn a pair in the typical paired-associate learning experiment could result either from direct rote associations requiring more time to form than indirect meaningful associations. Alternatively, subjects might eventually be memorizing most pairs by mnemonic devices in both cases, but simply taking longer to accomplish this in the typical paired-associate experiment for two reasons. First, because of the absence of instructions to use mnemonic devices, subjects are less efficient in generating mnemonics. Second, the structure of a paired-associate learning procedure limits the time to think of a mediator for a pair on any given trial.

A study by Bugelski, Kidd, and Segman provides an estimate of the time required to generate useful image mediators in a serial learning context. In all conditions of the experiment, the task was to learn a list of ten common words in the correct serial order. The words were presented at one of the three rates: two, four, or eight seconds per item. Subjects in the experimental group learned a mnemonic device for memorizing serial lists that involved memorizing a list of ten words that rhymed with the names of the digits one through ten: "One is a bun, two is a shoe, three is a tree, four is a door, five is a hive, six is sticks, seven is heaven, eight is a gate, nine is wine, and ten is a hen." As each word in any particular list was called out, the subjects were to generate a mediating word for its serial position and generate a visual image integrating the mediating word associated with the position and the test word presented at that position. For example, if the third word in the list was *knife*, subjects in the mnemonic condition were to generate the mediating word *tree* associated with serial position *three* and form a common image for *knife* and *tree* such as a "knife sticking into a tree." At the eight-second rate of presentation, this visual-image mnemonic resulted in a substantial facilitation of the amount remembered compared to the control condition in which the mnemonic was not used. However, no benefit whatsoever resulted from the mnemonic when words were presented at the two-second rate, because two seconds is not enough time to generate the rhyming word and integrate the two words into a visual image that benefits learning. Somewhere between four and eight seconds appears to be necessary under the conditions of this experiment.[9]

When subjects are presented with pictures to be remembered rather than required to generate them, a substantial level of learning is obtained with a study time of one or two seconds per picture. Potter and Levy studied recognition memory for pictures of such things as outdoor scenes, interiors, people, animals, and food, avoiding similar pictures. Subjects were shown a film containing 16 different pictures presented at a rate ranging from a tenth of a second per picture up to two seconds per picture. Following presentation of the 16 pictures, recognition memory for these pictures was tested by presenting the 16 pictures mixed randomly with 16 new pictures. Subjects were required to decide "yes" or "no" regarding whether each test picture was in the previously presented set. The probability of correctly identifying a previously presented picture, along with the false recognition rate for new pictures, as a function of the study time per picture is shown in Figure 13-1.[10]

Of course in this case the retention intervals were very short, since the recognition memory test occurred immediately following presentation of each set of 16 pictures. At such short retention intervals, a two-second study time per picture achieves almost a maximum recognition memory performance. A greater amount of study time might be necessary to achieve a level of strength sufficient to last for a longer retention interval and overcome greater amounts of retroactive interference. Nevertheless it is clear that a substantial level of acquisition of image memory for pictures can be achieved with study times on the order of two seconds, and some degree of learning is achieved even with study times as short as one-eighth of a second per picture.

Figure 13-1 suggests a gradual increase in acquisition of the image memory trace with increasing study time, but remember that such apparently incremental average curves could result from very abrupt, all-or-none learning processes occurring after randomly varying amounts of study time. Furthermore, a picture consists of a number of parts, and the increase in trace strength in Figure 13-1 might result from an all-or-none learning process for each of the component parts of the picture. From this standpoint, whether one views acquisition of a memory trace as all-or-none or incremental may depend upon how finely one wishes to analyze the

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[9] B. R. Bugelski, E. Kidd, and J. Segman, "Image as a Mediator in One-Trial Paired-Associate Learning." *Journal of Experimental Psychology*, 1968 (76), 69-73.

[10] M. C. Potter and E. I. Levy, "Recognition Memory for a Rapid Sequence of Pictures." *Journal of Experimental Psychology*, 1969 (81), 10-15.

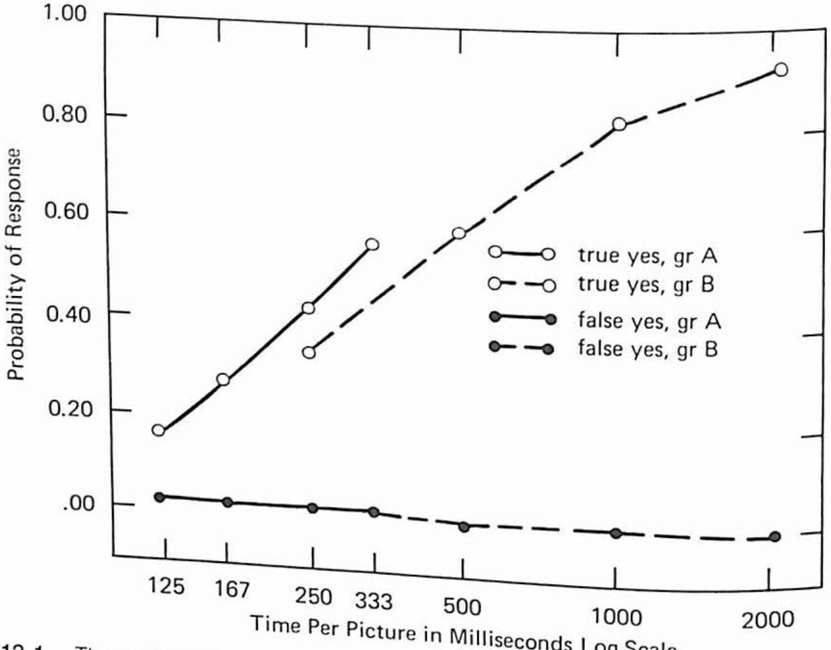

Figure 13-1. The probability of responding "yes" to an old picture and "yes" to a distractor at each rate of presentation in Potter and Levy's experiment. (Copyright 1969 by the American Psychological Association. Reprinted by permission.)

acquisition process. From the most molar point of view, both acquisition and forgetting appear to be incremental, but the all-or-none or incremental character of the memory trace at more molecular levels is still undetermined.

Level of Acquisition and Forgetting Rate

The major focus in most experimental studies of acquisition dynamics has been explicitly or implicitly on the level of memory strength achieved after different amounts of study time, but it is logically possible to distinguish between two different effects on the memory trace of increasing acquisition time: (1) higher initial level of acquisition (degree of learning), and (2) lower subsequent forgetting rate for such material, as measured over a retention interval.

The dynamics of acquisition would be particularly simple to describe if the only effect of longer study times was to raise the initial level of acquisition without any effect on the subsequent forgetting rate. There are experimental studies relevant to this issue, but they do not present a consistent picture. We can say with some confidence (largely on the basis of a priori plausibility but also with some experimental support) that increasing the level of acquisition does not produce faster forgetting. The forgetting rate either remains invariant or decreases *with increasing level of acquisition*. Unfortunately, some experiments support invariance and some support a decrease in forgetting rate with increasing level of acquisition.[11] Furthermore, comparisons of forgetting rate for conditions with different degrees of learning are complicated by the fact that what one obtains as a measure of *forgetting rate depends critically on one's choice of a measure of memory strength*. There are many cases where one can come up with any of the three possible relations between degree of learning and forgetting rate (increasing, invariant, or decreasing) from the same set of data by choosing various commonly employed measures of memory strength. In the absence of an established theory of memory dynamics, there is no way to know which measure of memory strength to use.

The discrepant findings can be resolved by the following hypothesis. First one assumes that there is no intrinsic relationship between level of acquisition and subsequent forgetting rate, that forgetting rate is truly invariant with the level of acquisition. However, increasing study time frequently results in a change in the nature of encoding, which may result in a trace with a lower forgetting rate. For example, increasing study time may permit the subject to generate a visual or verbal mnemonic. Such mnemonically learned associations may be less similar to material processed in the retention interval and therefore be less affected by retroactive interference.

Mnemonics and Forgetting Rate

Embedding a pair of words into a common image or sentence clearly facilitates *learning* the association between the words, but does it also facilitate retention? A number of studies have claimed to find slower forgetting for mnemonically encoded material. Bower and Clark found a dramatic difference in long-term retention that favored mnemonic encoding of lists of words into a narrative story over any encoding used by control subjects. Both groups had the same amount of study time and both recalled the list of words perfectly on an immediate retention test, but on the delayed retention test (about 15-20 minutes later) the subjects who had made up narrative stories recalled 93 percent of the words, while the control subjects recalled only 13 percent.[12]

Bower and Clark's study is not definitive because degree of learning was not necessarily equal for the two groups. When one obtains close to perfect performance by two groups on an immediate retention test, the groups might have vastly different degrees of overlearning to which the percent correct measure is insensitive. To my knowledge no study claiming superior retention for mnemonically encoded material has adequately equated initial degree of learning. In this regard one must note the important point made by Underwood that groups that differ in speed of learning cannot be equated for degree of learning merely by running to a common criterion in a standard paired-associate or serial anticipation task.[13] The group that learned faster—in this case the mnemonic group—will have learned more from the feedback on the last (criterion) learning trial and will therefore have a greater degree of learning than the other group.

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[11] Peterson and Peterson, "Short-Term Retention." Hellyer, "Supplementary Report." W. A. Wickelgren and D. A. Norman, "Invariance of Forgetting Rate with Number of Repetitions in Verbal Short-Term Recognition Memory." *Psychonomic Science,* 1971 (22), 363-64. W. A. Wickelgren, "Trace Resistance and the Decay of Long-Term Memory." *Journal of Mathematical Psychology,* 1972 (9), 418-55.

[12] G. H. Bower and M. C. Clark, "Narrative Stories as Mediators for Serial Learning." *Psychonomic Science,* 1969 (14), 181-82.

A study of forgetting by Olton best controlled for degree of learning in the mnemonic versus the control group. Olton found no difference in forgetting rate, although embedding both words of a pair into a sentence substantially increased the rate of learning.[14]

What is one to make of this? There has not yet been enough methodologically sound work to come to a definite conclusion, but based on what we know generally about learning and memory, mnemonic encoding should reduce susceptibility to interference more than rote encoding, if rote encoding means phonetic or graphic encoding. However, subjects in the rote control condition (given standard paired-associate or serial learning instructions) may eventually encode the material in much the same way that mnemonically instructed subjects do. Forming images or propositions may be essential to achieving a high criterion of learning in paired-associate and serial learning tasks. Phonetic or graphic encoding may be so affected by interference that a subject cannot reach even a modest criterion of learning without using mnemonic encoding. If so, then at equivalent degrees of learning the qualitative nature of the coding is equivalent too and no differences in retention could be observed.

Furthermore, differences in forgetting are to be expected if there are substantial sources of interference. If most of the forgetting over some retention interval is the consequence of temporal decay, there is no reason to expect slower forgetting for mnemonically encoded material. As we shall see in Chapter 14, there is good reason to believe that most of the forgetting that occurs over retention intervals of less than a few days is the result of decay, unless subjects are required to learn highly similar material during the retention interval.

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[13] B. J. Underwood, "Speed of Learning and Amount Retained: A Consideration of Methodology." *Psychological Bulletin*, 1954 (51), 276-82. B. J. Underwood, "Degree of Learning and the Measurement of Forgetting." *Journal of Verbal Learning and Verbal Behavior*, 1964 (3), 112-29. See also L. Postman, "Does Imagery Enhance Long-Term Retention?" *Bulletin of the Psychonomic Society*, 1974 (3) 385-87.

[14] R. M. Olton, "The Effect of a Mnemonic upon the Retention of Paired-Associate Verbal Material." *Journal of Verbal Learning and Verbal Behavior*, 1969 (8) 43-48.

The Application of Mnemonic Methods to Education

The many laboratory demonstrations of the effectiveness of imagery and sentence mnemonics in paired-associate learning have led to improved methods of foreign-language vocabulary learning. Such vocabulary learning is a pretty direct real-life analogue of paired-associate learning, and Atkinson and Raugh have shown that mnemonic methods can substantially speed up learning of both Russian-English and Spanish-English vocabulary pairs. In the Russian-English study the increase in the effectiveness of the mnemonic method over the control group (not instructed in mnemonic techniques) was 50 percent; in the Spanish-English study it was over 200 percent! You can learn foreign-language vocabularies by rote rehearsal, but it would obviously be wise for you to try to use a mnemonic method. Atkinson and Raugh suggest the *keyword method*. First you pronounce the foreign word (for example, the Spanish word *caballo*, pronounced *cob-eye-yo*, meaning *horse*) and think of an English keyword strongly associated to it, perhaps by phonetic similarity (such as *eye*). Then you think of a visual image or sentence that relates the English keyword (*eye*) and the English translation (*horse*) in some way. You might imagine a horse with one enormous eye in the middle of its forehead or a horse kicking someone in the eye.[15] (You will not soon forget that last image, though you might like to!) Most people who have learned foreign-language vocabularies have used something close to the keyword method for many word pairs, but using this method right away for all pairs greatly speeds learning.

LEVELS OF PROCESSING

As we have already noted, encoding at the lower structural levels, such as the phonetic or graphic levels, should be associated with greater susceptibility to interference from processing subsequent stimuli than encoding at higher semantic and image-operational levels. This means that under most circumstances the forgetting rate for traces stored at lower levels will be more rapid than the forgetting rate for traces stored at higher levels. The higher the level of processing, the more distinctively the stimulus has been encoded and therefore the less likely it is to be similar to subsequently processed stimuli. Lower similarity to subsequent material implies less retroactive interference and therefore slower forgetting under many circumstances.

This theory is approximately the same as that advanced by Craik and

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[15] For a review see R. C. Atkinson, "Mnemotechnics in Second-Language Learning," *American Psychologist*, 1975 (30), 821-28.

Lockhart.[16] Their "levels-of-processing" model has definite advantages over earlier multistore theories, such as those that distinguish between short-term memory and long-term memory. In the first place, in the levels of processing theory only one dynamic type of trace and one set of acquisition, storage, and retrieval laws are required. Second, differences in forgetting rate derive from a common law of interference producing different amounts of interference depending on the distinctiveness of encoding at the different levels of processing. Third, the hypothesis of many different degrees of encoding distinctiveness is more compatible with the apparently continuous variation in the forgetting rate found for different types of materials under different conditions. If only two different forgetting rates had been found, the case for a simple dichotomy between short-term and long-term memory would have been strong. However, since the forgetting rate appears to be almost continuously variable over a substantial range, the multiple-levels-of-processing approach appears much more compatible with the data. Finally, the levels-of-processing notion is easily generalizable to an encoding distinctiveness hypothesis in which the greater the redundancy of encoding and the greater the uniqueness of the chunks used to encode a stimulus, the less subject the trace is to interference and therefore the longer it will be remembered. Other phenomena that are consistent with the levels-of-processing or encoding distinctiveness hypothesis will be discussed in the remainder of this section.

Repetition and Rehearsal Time

According to the encoding distinctiveness hypothesis, additional study time may be used in one of two rather different ways: (1) It might be used merely to rehearse the trace using the initial type of encoding. For example, a word might be encoded at a phonetic level and added study time used merely to rehearse the word at that phonetic level. (2) It might be used for recoding the stimulus at, say, a higher semantic level. Thus with the added study time one might strengthen associations between the word and one or more of the semantic categories that it belongs to.

In free recall the retrieval organization provided by recalling categories and then recalling the words within each category is very important to a high level of performance, so continued rote rehearsal of words at a lower structural level is vastly less effective than using the time to process the material at a higher semantic level by categorizing the words and thereby strengthening the associations from category concepts to the words to be recalled. In some cases time spent in mere rehearsal without generating additional codes (new associations) has failed even to significantly raise the level of acquisition, let alone affect the decay rate.[17] It is quite possible that continued increases in degree of acquisition are obtained with increasing study time more from continued generation of new ways of encoding the material than from continued strengthening of the same trace. When only a single encoding is used by subjects, the point of diminishing returns in degree of learning may be reached rather quickly with increased study time.

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[16] F. I. M. Craik and R. S. Lockhart, "Levels of Processing: A Framework for Memory Research." *Journal of Verbal Learning and Verbal Behavior*, 1972 (11), 671-84.

Speed Reading and Retention

Proponents of speed reading claim that you can drastically increase your reading speed without loss of comprehension. According to the levels-of-processing hypothesis, the more rapidly material is processed the less time is available for distinctive encoding, and therefore the more rapidly the material will be forgotten. As we have discussed, this has been amply verified by experimental studies in other contexts. Direct studies of retention after reading at different speeds indicate that a faster reading speed is associated with poorer comprehension and poorer retention of the material.[18]

Of course there are many circumstances in which one does not need to acquire and retain very much of what one reads, when a rapid skimming of the material is enough to get what one wants. Furthermore, once one makes whatever decisions are contingent upon what is being read, sometimes there is no further need to remember the material. Under such circumstances rapid forgetting is an advantage rather than a disadvantage, since it reduces the potential for associative interference of that material with other material. For such purposes it can be a decided advantage to develop the speed reading (skimming) skill, and for many people the development of such skill might well be worth the cost. The important thing is to know what skill you are acquiring, what its advantages and disadvantages are, and therefore when to use it and when not to use it.

The critical thing for most of the material you learn in school is to understand it, which means encoding it in a way that makes it distinctive from unrelated material and related to all of the things it ought to be related to in order for you to use it. Understanding probably means nothing more or less than the development of such an adequate encoding of material into memory. Once one has understood the material—that is, encoded it in this way—the learning of it has already occurred automatically, without any strain or even a conscious intention to learn. This type of encoding takes time. The time you spend thinking about material you are reading and relating it to previously stored material is about the most useful thing you can do in learning any new subject matter. From this standpoint reading speed measured in words per minute is of little consequence. What matters is the speed with which you are forming relevant new associations between the material you are reading and concepts and propositions in your associative memory.

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[17] V. Modigliani and J. G. Seamon, "Transfer of Information from Short- to Long-Term Memory." *Journal of Experimental Psychology*, 1974 (102), 768-72. G. F. Meunier, D. Ritz, and J. A. Meunier, "Rehearsal of Individual Items in Short-Term Memory." *Journal of Experimental Psychology*, 1972 (95), 465-67. F. I. M. Craik and M. J. Watkins, "The Role of Rehearsal in Short-Term Memory." *Journal of Verbal Learning and Verbal Behavior*, 1973 (12), 599-607. A. E. Woodward, Jr., R. A. Bjork, and R. H. Jongeward, Jr., Recall and Recognition as a Function of Primary Rehearsal." *Journal of Verbal Learning and Verbal Behavior*, 1973 (12), 608-17. D. L. Roenker, "Role of Rehearsal in Long-Term Retention." *Journal of Experimental Psychology*, 1974 (103), 368-71.

[18] R. P. Carver, "Speed Readers Don't Read; They Skim." *Psychology Today*, August 1972, pp. 22-30. R. C. Graf, "Speed Reading: Remember the Tortoise." *Psychology Today*, December 1973, pp. 112-13.

Incidental and Intentional Learning

In an intentional learning paradigm subjects know while being exposed to some material that memory for the material will later be tested. In an incidental learning paradigm subjects must process the material in some manner, but they are not aware during original exposure to the material that retention will be tested later. One conclusion that has been reached in comparisons of incidental and intentional learning is that the *intent to learn* is unimportant to level of acquisition and subsequent forgetting. Intentional learning instructions are effective in facilitating learning only to the extent that they cause subjects to process material in a manner different from the way they process in the incidental condition, and that this difference establishes stronger or longer-lasting memory traces.[19] It is the type of processing that determines the type of memory traces established, in a relatively automatic and unconscious manner, independent of whether a subject is trying to learn the material being processed.

This hypothesis that intent to learn is unimportant should be regarded as tentative, but it appears to be a reasonable working hypothesis that memory traces are established automatically during mental processing. The type of memory trace acquired depends upon the type of mental processing. In particular, long-lasting semantic memory traces will not be formed, if processing is completely at a phonetic level.

Tresselt and Mayzner studied free recall of a list of words in an incidental learning paradigm as a function of three different orienting tasks: crossing out vowels, copying the words, and judging the extent to which each word was an example of the concept "economic." Free recall of the words following the semantic orienting task was twice as high as recall following the word-copying task, which in turn was twice as high as recall following the letter-processing task. This is consistent with the hypothesis that the higher the level of processing of the material, the greater the degree of learning or the slower the rate of forgetting or both. Studies by Hyde and Jenkins and Johnston and Jenkins support the same conclusion—that processing of verbal material at lower phonetic levels leads to weaker or less persistent traces than processing material at higher semantic levels.[20]

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[19] L. Postman, "Short-Term Memory and Incidental Learning," in A. W. Melton (ed.), *Categories of Human Learning*. New York: Academic Press, 1964, pp. 145-201. J. J. Jenkins, "Remember That Old Theory of Memory? Well Forget It." *American Psychologist*, 1974 (29), 785-95.

Bower and Karlin have shown that the more extensively a picture of a face is processed, the greater the subsequent recognition memory of the face. If subjects were required to make a relatively superficial judgment during initial acquisition, such as the person's sex, subsequent recognition memory was poorer than if subjects were required to make a more complex judgment, such as likableness or honesty. The same relationship held true under both intentional and incidental learning instructions. Also, as is frequently found, there was no significant difference between intentional and incidental learning instructions. It is the mode of processing of input that is important, and when this is controlled, intent to learn is either much less important or totally unimportant.[21]

Of course level of processing not only determines how much we remember, but also what properties of the input are remembered. In Chapter 10 we discussed the classic study by Sachs and related studies in which processing of connected discourse largely at the semantic level produced long-lasting memory for the meaning of sentences but virtually no memory for the particular words or syntactic structure of the sentences. Under other conditions, where the attention of the subject is focused on lexical and syntactic aspects of sentences, these lexical and syntactic properties can be remembered for substantial periods of time, although not so well as semantic information, since there is an intrinsic difference in the susceptibility to interference.

SPACING EFFECTS

Some years ago several experiments demonstrated that learning of serial or paired-associate lists often took fewer trials if a rest interval of a minute or two intervened between each trial—the spaced or distributed-practice condition. If one counted the time between trials as a part of the total learning time, the time required to reach a common learning criterion, such as one perfect recitation of the list, was not necessarily favorable to spaced practice, but the total number of learning trials was generally smaller with spaced than with massed practice. Underwood demonstrated that this benefit occurs despite the fact that greater forgetting occurs between trials in the spaced-practice condition than in the massed-practice condition. When spacings are on the order of a minute or two, the greater learning on each trial of the spaced-practice condition appears to more than compensate for the greater between-trial forgetting.[22] So if one can make efficient use of the one-minute intervals, it would probably be a more efficient use of one's time to learn via spaced rather than massed practice.

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[20] M. E. Tresselt and M. S. Mayzner, "A Study of Incidental Learning." *Journal of Psychology*, 1960 (60), 339-47. T. S. Hyde and J. J. Jenkins, "Differential Effects of Incidental Tasks on the Organization of Recall of a List of Highly Associated Words." *Journal of Experimental Psychology*, 1969 (82), 472-81. C. D. Johnston and J. J. Jenkins, "Two More Incidental Tasks That Differentially Affect Associative Clustering in Recall." *Journal of Experimental Psychology*, 1971 (89), 92-95.

[21] G. H. Bower and M. B. Karlin, "Depth of Processing Pictures of Faces and Recognition Memory." *Journal of Experimental Psychology*, 1974 (103), 751-57.

More recently the spacing effect has been studied in a wide variety of more molecular learning and memory paradigms that test retention after only one or two presentations of an item. Beneficial effects of increased spacing of two learning trials have been obtained with the free-recall paradigm, continuous recognition memory, continuous paired-associate recall memory, and the distractor paradigm of short-term memory.[23] Thus, the effect would appear to be an extremely robust one, independent of variations in the paradigms and conditions.

Numerous hypotheses have been advanced to explain the spacing effect on acquisition. If we confine our focus to the more molecular studies, the ones that have employed only two learning trials to investigate the spacing effect, we can divide explanations of the beneficial effect of greater spacing of two learning trials into three categories: (1) those that attribute the effect to better learning or consolidation produced by the first repetition, (2) those that attribute the effect to superior learning produced by the second repetition, and (3) those that attribute the effect to a greater probability of differential encoding on the two acquisition trials.

Existing evidence makes it clear that the beneficial effects of spaced presentation are not the result of increased time for rehearsal of the first repetition. Bjork and Allen demonstrated that filling the interval between the first and second presentations with a more difficult interpolated task in no way attenuated the spacing effect. In fact, very slightly better memory performance was obtained when a difficult task intervened between the first and second repetitions than when an easy task intervened.[24] If the beneficial effects of spacing were the product of rehearsal of the first repetition, one would expect the reverse result.

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[22] B. J. Underwood, "Ten Years of Massed Practice on Distributed Practice." *Psychological Review,* 1961 (68), 229-47. McGeoch and Irion, *The Psychology of Human Learning,* pp. 138-93.

[23] D. L. Hintzman, "Theoretical Implications of the Spacing Effect," in R. L. Solso (ed.), *Theories in Cognitive Psychology: The Loyola Symposium.* New York: Wiley, 1974, pp. 77-79.

[24] R. A. Bjork and T. W. Allen, "The Spacing Effect: Consolidation or Differential Encoding?" *Journal of Verbal Learning and Verbal Behavior,* 1970 (9), 567-72.

Hintzman and Rogers demonstrated the typical spacing effect with memory for pictures that are difficult to rehearse and do not appear to benefit from the opportunity for visual rehearsal (see Chapter 14).[25]

Furthermore, there is some evidence that the spacing effect in acquisition is not because of superior unconscious consolidation of the first repetition, but because of superior learning of the second repetition the greater the spacing between it and the first repetition. In the attempt to determine whether the spacing effect resulted from superior learning or consolidation of the first or the second presentation, Hintzman, Block, and Summers attempted to tag each presentation separately by using different modalities (visual or auditory). Subjects were asked to make a number of memory judgments such as the frequency of occurrence of different words (zero, one, or two) and the modality of presentation of each occurrence. Focusing on the modality judgments, which constituted the tag for each presentation, the evidence indicated that close spacing tended to reduce memory for the modality of the second presentation and had no effect on memory for the modality of the first presentation.[26] Thus if memory for the modality of an event is correlated with the amount of memory for the event in general, the spacing effect appears to be the result not of a reduction in consolidation of the first occurrence but rather of a lower level of acquisition of the second occurrence, the more closely it follows the first.

There have been some attempts to attribute the spacing effect to a greater encoding variability on the two learning trials, the greater the spacing—that is, that subjects encode the same word differently on its two occurrences and that the probability of this increases with increased spacing. This hypothesis assumes that encoding variability is beneficial for learning, that a higher level of learning or a slower rate of forgetting is obtained for two different encodings of an item than for a repetition of the same encoding. Hintzman has reviewed the evidence with respect to the encoding variability explanation of the spacing effect and come to the conclusion that one version of this hypothesis appears untenable but that another is not contradicted by the known information, though there is very little direct support for it.[27] It seems best to suspend judgment about the role of encoding variability in the spacing effect.

For a time it was thought that spaced practice produced superior retention as well, until Underwood and his colleagues performed a series of experiments controlling degree of learning by using a larger number of learning trials in the massed practice condition to achieve the same learning criterion as in the spaced practice condition and found that spaced practice had little or no beneficial effect on subsequent retention.[28] Now the pendulum is swinging in the other direction. Keppel distributed learning over a four-day period, with two learning trials per day in the spaced-practice condition compared to massing all eight trials in one learning session on the same day. When he measured retention immediately and after one and eight days, he found that with such a large degree of spacing between learning trials, forgetting following distributed practice was enormously slower than forgetting following massed practice, despite the fact that a lower final degree of learning was achieved in the spaced as opposed to the massed practice condition, as measured by the immediate retention test following the last learning trial.[29] (One might note in passing that Keppel's findings constitute another refutation of the hypothesis that higher degrees of learning are inevitably associated with slower forgetting rates.)

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[25] D. L. Hintzman and M. K. Rogers, "Spacing Effects in Picture Memory." *Memory and Cognition*, 1973 (1), 430-34.

[26] D. L. Hintzman, R. A. Block, and J. J. Summers, "Modality Tags and Memory for Repetitions: Locus of the Spacing Effect." *Journal of Verbal Learning and Verbal Behavior*, 1973 (12), 229-38.

[27] Hintzman, "Theoretical Implications of the Spacing Effect."

Some special features of Keppel's experiment deserve mention. Keppel created a substantial amount of proactive interference by having subjects learn three *AB*, *AC*, *AD* lists before learning the critical *AE* list under either massed or distributed practice. This heavy degree of proactive interference may contribute to the magnitude of the difference in retention of *AE* list learning between the spaced and massed practice conditions. Keppel also compared retention under distributed practice (*DP*) with two massed practice conditions, one in which subjects learned the fourth *AE* list on the same day as they learned the three prior lists (*MPs*) and one in which they learned it three days later (*MPd*). Under the distributed practice conditions subjects had the first two trials on the same day as the three prior lists and then two additional trials on each of the next three days. Thus, the two massed practice conditions provide a control for time interval between learning the three proactive interference lists and learning the test list. As can be seen in Figure 13-2, delaying massed practice learning of the fourth list until the third day following learning of the three prior lists did slightly reduce the subsequent forgetting of the fourth list, but this effect was small in relation to the enormous reduction of the forgetting rate caused by spaced practice.

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[28] For a review of the idea that spaced practice produced superior retention, see McGeoch and Irion, *The Psychology of Human Learning*, pp. 156-58. B. J. Underwood and J. Richardson, "Studies of Distributed Practice: XIII. Interlist Interference and the Retention of Serial Nonsense Lists." *Journal of Experimental Psychology*, 1955 (50), 39-46. B. J. Underwood and J. Richardson, "Studies of Distributed Practice: XVII. Interference and the Rentention of Paired Consonant Syllables." *Journal of Experimental Psychology*, 1957 (54), 274-79. B. J. Underwood and R. W. Shulz, "Studies of Distributed Practice: XX. Sources of Interference Associated with Differences in Learning and Retention." *Journal of Experimental Psychology*, 1961 (63), 228-35.

[29] G. Keppel, "Facilitation in Short- and Long-Term Retention of Paired Associates Following Distributed Practice in Learning." *Journal of Verbal Learning and Verbal Behavior*, 1964 (3), 91-111.

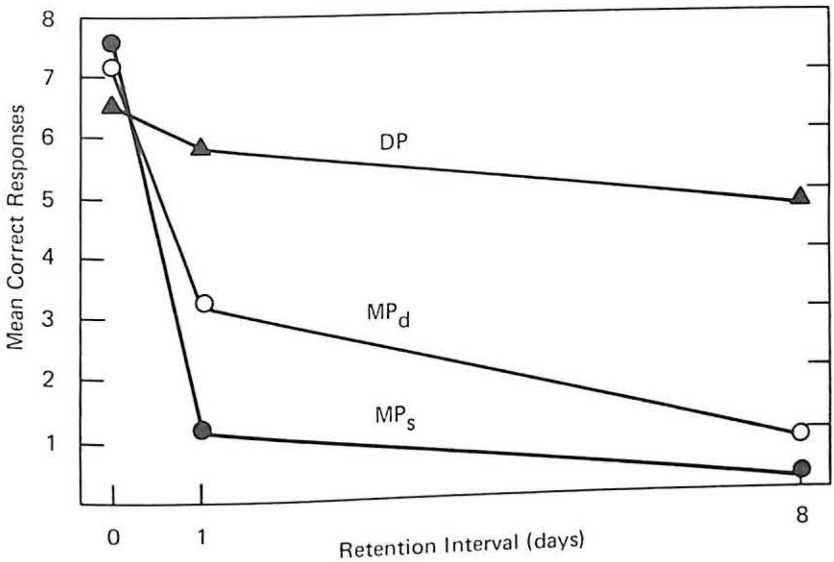

Figure 13-2. Retention following learning by distributed (*DP*) vs. massed (*MPd* + *MPs*) practice (from Keppel by permission).

Most of the studies that have failed to find a facilitative effect of spaced practice on retention are those where the total time between the first and last learning trials was not very different under the massed and spaced practice conditions. The reason for this is that a larger number of learning trials were required in the massed practice conditions to achieve the same learning criterion as in the spaced practice condition, so from this viewpoint there was little difference in the degree of temporal dispersion of learning in these comparisons. Most of the successful demonstrations of a facilitative effect of spaced practice on retention are those in which learning was distributed over a greater total learning period, such as in the study by Keppel. Furthermore, the Keppel experiment demonstrates that the superior retention produced by spaced practice is in no way because spaced practice produces a higher initial degree of learning than massed practice.[30]

RELEARNING

An old adage concerning human memory is that relearning of previously learned material will be faster than original learning of this material, even when you think you have completely forgotten the material. From a practical standpoint this is almost always true, because people usually underestimate how much they remember of a previously learned subject. If I estimate my memory for high school Latin vocabulary on the basis of the number of Latin-English word pairs I can freely recall I will grossly underestimate my memory for Latin vocabulary. Cued recall of the English translation, given a Latin word, provides a higher estimate, and recognition memory for Latin-English word pairs will give a still higher estimate. Recognition memory scores can be substantial when free recall is zero.

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[30] Underwood and Richardson, "Studies of Distributed Practice: XIII, XVII, and XX." Wickelgren, "Trace Resistance and Decay." Keppel, "Facilitation in Retention."

It is hardly surprising that relearning to some criterion is faster when the strengths of your memory traces are already closer to that criterion than in original learning. Virtually all laboratory studies of relearning have not used the most sensitive recognition test to assess the strength of memory traces prior to relearning. Also, in most relearning experiments memory performance was not at zero at the time of beginning relearning, even by a recall test. Hence, the greater speed of relearning than original learning in these cases can be simply attributed to starting from a higher level of trace strength.

It would be more surprising and of greater theoretical significance if relearning were faster when recognition memory scores were at chance. Some unpublished experiments of my own have given no support to this hypothesis. Relearning was not superior to original learning, nor was retention following relearning any different than retention following original learning, when care was taken to wait long enough so that recognition scores were essentially at chance before beginning relearning. Tom Nelson, however, has found superior relearning of previously learned pairs that subjects had failed to recognize on a prior retention test.[31] Failure to recognize a particular pair does not necessarily mean that its trace strength is zero; it only means that its trace strength is below the criterion level of strength for a "yes" response. Such criteria are extremely variable, and being below the criterion does not mean having zero strength. It is much safer to study relearning after waiting so long that an entire population of previously learned pairs is recognized with no better than chance accuracy. Nelson's findings should thus be viewed with caution, but the results are suggestive, and the topic of relearning deserves much more systematic study than it has received.

PROACTIVE INTERFERENCE

Proactive interference is traditionally defined as a negative effect of prior learning on the *retention* of subsequent learning. I was taught to distinguish sharply between proactive interference and *negative transfer*, which is a negative effect on the *acquisition* of a list owing to prior learning of similar material. There is no question about the importance of distinguishing the effects of a variable on acquisition from its effects on retention, however such distinctions between acquisition and retention need to be made for every variable that affects learning and memory performance, and in my opinion it is easier to keep that general rule in mind than to generate different names to differentiate the effect of every variable on acquisition and retention. Hence, the term proactive interference will be used here to refer to the effects of prior learning on *both* subsequent learning and the retention of that subsequent learning.

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[31] T. O. Nelson, "Savings and Forgetting from Long-Term Memory." *Journal of Verbal Learning and Verbal Behavior,* 1971 (10), 568-76.

Our understanding of the nature of proactive interference has been greatly advanced by findings that indicate that prior learning of an *AB* pair has no effect on the rate of forgetting for a subsequently learned (similar) *AC* pair, as measured by recognition tests.[32] As we shall see in Chapters 14 and 15, recognition is less affected by some of the retrieval interference factors that affect recall. For example, when a subject attempts to recall the associate of *A* on the second list, there may be competition between the *B* and *C* items. Such competition is known to increase with increasing retention interval, as the subject gradually forgets which item, *B* or *C*, was in the first list and which in the second. As discussed earlier in this chapter and further in Chapter 14, subjects appear to develop a set to produce the responses in the list that they are currently learning and to suppress any previously established response sets for the same stimuli. During the retention interval following second-list learning, the set for the second-list responses diminishes and that for the first-list responses recovers. Such changes in response set and decreases in list differentiation with increasing retention interval apparently cause the faster forgetting (using recall tests) of the *AC* list when it is preceded by a similar *AB* list than when it is learned in isolation or preceded by a dissimilar—*DB*—list.[33] Thus, the faster forgetting of a target list preceded by a similar list (proactive interference effect on retention) is a phenomenon limited to recall tests of memory and is not found on recognition tests. Hence, there is no reason to believe that the basic storage dynamics for *AC* associations is in any way affected by the presence of previously learned *AB* associations.

There is however a rather consistently observed negative effect of prior learning on the acquisition of subsequent similar associations—that is, the degree of learning for some material is typically lower when it has been preceded by the learning of similar material than when it is preceded by learning of rather different material (to control for general practice effects on learning). This proactive interference effect on learning is not always obtained,[34] but it has happened often enough to indicate that there is some negative effect on subsequent learning of prior similar learning.

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[32] L. Postman, K. Stark, and J. Fraser, "Temporal Changes in Interference." *Journal of Verbal Learning and Verbal Behavior*, 1968 (7), 672-94. W. A. Wickelgren, "Single-Trace Fragility Theory of Memory Dynamics. *Memory and Cognition*, 1974 (2), 775-80.

[33] B. J. Underwood, "Interference and Forgetting." *Psychological Review*, 1957 (64), 49-60.

Some of the biggest and most consistent effects have turned up in studies of short-term verbal memory. Keppel and Underwood demonstrated that the item presented on the first trial of an experiment is better learned or remembered or both over retention intervals varying from three to 18 seconds than the item presented on the second trial, which in turn is superior to the item presented on the third trial. By the fourth trial such proactive interference effects had appeared to reach a maximum, and performance did not subsequently deteriorate over later learning trials in the experiment.[35]

Wickens, Born, and Allan demonstrated that there could be release from this proactive interference effect by changing the type of item to be remembered from trial i to trial $i + 1$ in a memory experiment. Thus, as illustrated in Figure 13-3, if a group remembering letter trigrams is switched to digit trigrams on trial 6, performance on trial 6 will be markedly superior to a group that learns digit trigrams throughout the experiment. Four groups are needed to control for differences in learning and memory because of different types of material as well as to control for whether the material is or is not shifted. The two experimental groups are shifted either from letters to digits or from digits to letters, and the two control groups have either letters or digits throughout.[36] Considerable release from proactive interference is obtained by shifting to different material to be remembered. Furthermore, a considerable release from proactive interference can be obtained merely by waiting for two minutes between memory trials.[37]

At least a portion of the primacy effect that can be obtained in short-term memory for serial lists is because there has been superior learning of the first item or two in the list. When rehearsal is controlled, the rate of forgetting for all items in a list appears to be the same, but there is a definite primacy effect in degree of learning, such that the first item acquires the greatest initial strength in memory, then the second, the third, and so on,

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[34] Wickelgren, "Single-Trace Fragility Theory."

[35] G. Keppel and B. J. Underwood, "Proactive Inhibition in Short-Term Retention of Single Items." *Journal of Verbal Learning and Verbal Behavior,* 1962 (1), 153-61.

[36] D. D. Wickens, D. G. Born, and C. K. Allen, "Proactive Inhibition and Item Similarity in Short-Term Memory." *Journal of Verbal Learning and Verbal Behavior,* 1963 (2), 440-45.

[37] L. R. Peterson and A. Gentile, "Proactive Interference as a Function of Time Between Tests." *Journal of Experimental Psychology,* 1965 (70), 473-78. H. Loess and N. C. Waugh, "Short-Term Memory and Intertrial Interval." *Journal of Verbal Learning and Verbal Behavior,* 1967 (6), 455-60. J. P. Kincaid and D. D. Wickens, "Temporal Gradient of Release from Proactive Inhibition." *Journal of Experimental Psychology,* 1970 (86), 313-16.

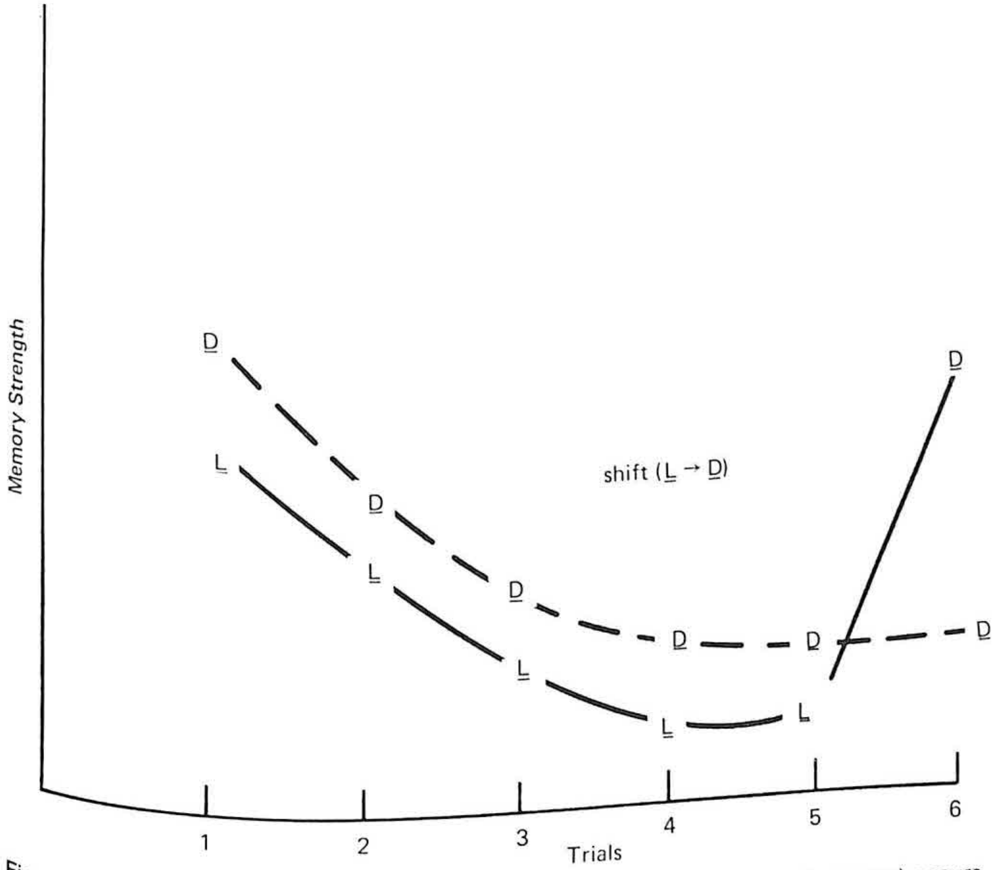

Figure 13-3. A build-up in proactive interference (reduction in memory performance) occurs over trials 1 to 5 with material of the same type, whether letter (*L*) or digit (*D*) trigrams. Release from this proactive interference (improved memory performance) is shown on trial 6 for the group shifted from letter trigrams to digit trigrams.

until an asymptote is reached at around the fourth item in a list.[38] It is not yet known whether intralist proactive interference effects have the same cause as interlist proactive interference effects.

It is possible that the explanation for reduced acquisition caused by proactive interference from similar material and reduced acquisition from massed presentation of the same material have a common mechanism. That is to say, one might assume that the negative effect on second-trial learning of having studied the same material just recently is but the extension to 100 percent similarity of the proactive interference effect of learning similar material in the recent past.

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[38] W. A. Wickelgren and D. A. Norman, "Strength Models and Serial Position in Short-Term Recognition Memory," *Journal of Mathematical Psychology*, 1966 (3), 316-47.

AROUSAL AND LEARNING

Variations in Arousal During Waking

One of the important factors influencing the degree of acquisition and/or forgetting is the state of arousal of the organism at the time of learning and shortly thereafter. As a crude generalization, low arousal during or immediately after learning is deleterious for long-term memory, and moderate to high arousal is beneficial, at least up to a point. For example, when drugs that act as depressants of the central nervous system (such as alcohol, chlorpromazine, ether, and nitrous oxide) are administered shortly before, during, or shortly after a learning experience, they impair some aspect of long-term memory formation or retention in both animals and humans. By contrast, central nervous system stimulants (that increase arousal) (such as amphetamine, caffeine, nicotine, picrotoxin, and strychnine) facilitate memory trace formation or retention or both when they are administered in close temporal proximity to the learning experience.[39] In addition, normal fluctuations in the degree of arousal evoked by some learning event, as measured by the galvanic skin response, correlate positively with the amount of long-term memory established by a learning experience, at least as measured by recall tests. Furthermore, long-term retention appears to be facilitated by experimentally induced increases in arousal at the time of learning, through the presentation of white noise, by requiring subjects to increase their muscle tension, and so on.[40]

The initial experiment in this series, by Kleinsmith and Kaplan, obtained some very startling results to the effect that material learned under high arousal was established at an initially lower level of learning than material learned under lower arousal but showed *reminiscence* (increase in memory over a retention interval), while the material learned under low arousal showed forgetting, so that the retention functions crossed. At longer retention intervals, material learned under high arousal was retained significantly better than material learned under low arousal, even though at short retention intervals the relationship was reversed.

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[39] J. L. McGaugh and R. G. Dawson, "Modification of Memory Storage Processes." *Behavioral Science,* 1971 (16), 45-63. H. Steinberg and A. Summerfield, "Influence of a Depressant Drug on Acquisition in Rote Learning." *Quarterly Journal of Experimental Psychology,* 1957 (9), 138-45. D. W. Goodwin, E. Othmer, J. A. Halikas, and F. Freeman, "Loss of Short-Term Memory as a Predictor of the Alcoholic 'Blackout'." *Nature,* 1970 (227), 201-2. F. N. Johnson, "The Effects of Chlorpromazine on the Decay and Consolidation of Short-Term Memory Traces in Mice." *Psychopharmacologica,* 1969 (16), 105-4. F. Leukel, "A Comparison of the Effects of ECS and Anesthesia on Acquisition of the Maze Habit." *Journal of Comparative and Physiological Psychology,* 1957 (50), 300-306.

[40] L. J. Kleinsmith and S. Kaplan, "Paired-Associate Learning as a Function of Arousal and Interpolated Interval." *Journal of Experimental Psychology,* 1963 (65), 190-93. L. J. Kleinsmith and S. Kaplan, "Interaction of Arousal and Recall Interval in Nonsense-Syllable Paired-Associate Learning." *Journal of Experimental Psychology,* 1964 (67), 124-26. E. L. Walker and R. D. Tarte, "Memory Storage as a Function of Arousal and Time with Homogeneous and Heterogeneous Lists." *Journal of Verbal Learning and Verbal Behavior,* 1963 (2), 113-19. M. J. Butter, "Differential Recall of Paired Associates as a Function of Arousal and Concreteness-Imagery Levels." *Journal of Experimental Psychology,* 1970 (84), 252-56. D. E. Berlyne, D. M. Borsa, M. A. Craw, R. S. Gelman, and E. E. Mandell, "Effects of Stimulus Complexity and Induced Arousal on Paired-Associate Learning." *Journal of Verbal Learning and Verbal Behavior,* 1965 (4), 291-99. D. E. Berlyne, D. M. Borsa, J. H. Hamacher, and I. D. V. Koenig, "Paired-Associate Learning and the Timing of Arousal." *Journal of Experimental Psychology,* 1966 (7), 1-6. B. S. Uehling and R. Sprinkle, "Recall of a Serial List as a Function of Arousal and Retention Interval." *Journal of Experimental Psychology,* 1968 (78), 103-6.

Reminiscence has sometimes been obtained in subsequent studies, but it is not the usual finding and to my knowledge has never been obtained using a recognition measure. Thus (as is typically true of reminiscence findings) considerable skepticism is in order concerning the reliability of the effect, to say nothing of its interpretation. There is undoubtedly no increase in the strength of the memory trace in storage for material learned under either high or low arousal, so that findings of reminiscence are generally either chance fluctuations or the result of some confounding with the effectiveness of memory retrieval at the shorter versus longer retention intervals. Both of these factors undoubtedly played a role in the Kleinsmith and Kaplan findings, since recall was rather close to chance at both short and long retention intervals and the high arousal material consisted of paired associates whose stimuli were emotionally loaded words.

The crossover effect is more common; low arousal and high arousal material are both forgotten, and high arousal material has a lower initial degree of learning but a slower forgetting rate. (See Figure 13-4.) However, the degree of learning established by high arousal material is not invariably lower than that established under low arousal.[41]

What is virtually always the case in recall studies is that material learned under high arousal has a lower rate of forgetting than material learned under low arousal, irrespective of whether the degree of learning is higher under low or high arousal. However, this difference in forgetting rate has been established using recall tests of memory, not recognition tests, and since recall tests are much more susceptible to retrieval interference factors than recognition tests, it cannot be concluded that material learned under high arousal has a lower forgetting rate in storage than a material learned under low arousal until this effect is confirmed by recognition tests, and some attempts to confirm this using recognition tests have failed.[42]

On the basis of both physiological and human experimental studies, it does appear that high arousal facilitates memory measured at long reten-

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[41] For a review see E. Levonian, "Retention over Time in Relation to Arousal During Learning: An Explanation of Discrepant Results." *Acta Psychologica*, 1972 (36), 290-321.

[42] C. H. D. Williams and G. Frincke, "Effects of Delayed Auditory Feedback on Immediate and Delayed Recall and Recognition." *Journal of Experimental Psychology*, 1968 (76), 273-6. W. A. Wickelgren, "Alcoholic Intoxication and Memory Storage Dynamics." *Memory and Cognition*, 1975 (3), 385-89.

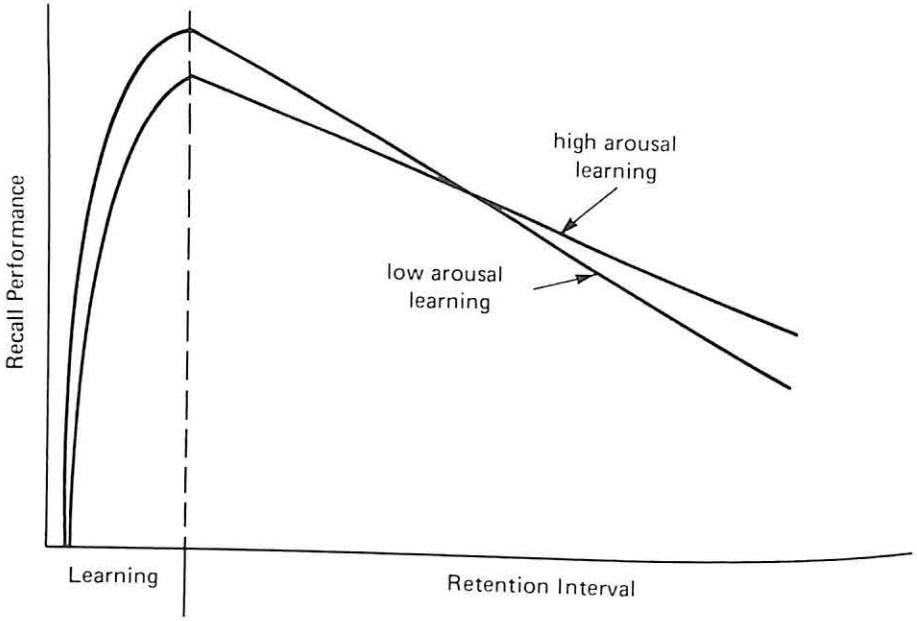

Figure 13-4. Crossover effect in retention of material learned under high versus low arousal. High arousal at the time of learning sometimes but not always produces slightly poorer learning, but it generally produces slower forgetting, as measured by recall tests.

tion intervals, but it is not yet possible to decide whether the effect is on degree of initial learning or subsequent rehearsal, rate of unconscious consolidation, or reduced susceptibility to the forces producing forgetting.

Sleep and Learning

The previous section was concerned with the effects of only moderate fluctuations in degree of arousal for waking organisms. The most extreme manipulation of arousal that typically exists in daily life is the fluctuation between the sleep and waking states. Some years ago there was a flurry of interest in whether human beings could learn while asleep. Devices were marketed that could present recorded material to the sleeping learner, and the person was supposed to learn virtually without effort. Such devices have great appeal to people who want something for nothing, and this turned out to be yet another fraud. When care was taken to insure that subjects were completely asleep as measured by electroencephalographic (EEG) recordings of brain waves, subsequent tests of recall and recognition of material presented while asleep showed no evidence of learning.[43]

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[43] W. H. Emmons and C. W. Simons, "The Non-Recall of Material Presented During Sleep." *American Journal of Psychology*, 1968 (69), 76-81. S. W. Keele, *Attention and Human Performance*. Palisades, Calif.: Goodyear, 1973, pp. 38-41.

However, the conclusions that sleep learning is impossible for auditorially presented verbal material should not be interpreted to exclude the possibility of all learning while asleep. It has been demonstrated that simple classical and even some kinds of instrumental conditioning are possible for human beings during sleep. When Beh and Barratt presented either a low or a high tone to sleeping subjects, the tones had no effect on brain waves as measured by the EEG. By contrast, a strong electrical shock produced a particular EEG pattern known as the *K*-complex. When the low tone was used as a *CS* paired with the shock *US*, the low tone eventually came to elicit the *K*-complex, while the high tone did not.[44] Thus, differential classical conditioning can occur during sleep. Furthermore, the conditioned response established during sleep transferred to the waking state.

Even instrumental conditioning can apparently occur during sleep. Weinberg presented a high tone to sleeping subjects, followed in 15 seconds by a loud bell that awakened them. Subjects could prevent the ringing of the bell by closing a switch in the 15-second interval after the high tone. After several weeks of training in a few nights each week, subjects gradually acquired the instrumental switch-closing response to the high tone.[45]

I have no quarrel with the demonstration of classical conditioning during sleep, but it is likely that only very special types of instrumentally conditioned responses can be established during sleep. For instance, in the Weinberg experiment the loud bell may very well elicit reflexive clenching of the hand that will occasionally result in switch closures. To the extent that the bell served as a *US* eliciting the switch closure response as a *UR*, the Weinberg experiment would actually be a demonstration of classical conditioning. As we have seen in the case of autoshaping (Chapter 2), the distinction between classical and instrumental conditioning is not always completely clear.

In any event it appears useful to distinguish between higher conceptual learning and lower-order conditioning in discussing the possibility of learning during sleep, as Keele pointed out.[46] Some types of conditioning appear to be possible during sleep, but higher-level conceptual learning induced by external stimulation is impossible in any practical sense. However, Keele has also pointed out that this conclusion must be tempered by some consideration of memory for dreams. Dreams contain high-level verbal thinking and visual imagery. Dreams also frequently produce rapid eye movements and EEG changes. These indices of dreaming activity have demonstrated that everyone spends a substantial amount of time dreaming every night. Typically, we recall very little of it the next day, but we can remember dreams in detail if we make a deliberate effort to remember them by writing down whatever we were dreaming about just before we awoke, so obviously some memory is established during the dreaming state and can be recalled during the subsequent waking state.

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[44] H. C. Beh and P.E.H. Barratt, "Discrimination and Conditioning During Sleep as Indicated by the Electroencephalogram." *Science*, 1965 (147), 1470-71.

[45] H. Weinberg, "Evidence Suggesting the Acquisition of Simple Discrimination During Sleep." *Canadian Journal of Psychology*, 1966 (20), 1-11.

[46] Keele, *Attention and Human Performance*.

The retention of dreams may not be so short lived as it is usually thought to be. Considering the associative character of longer-term memory, we would not typically recall dream contents without appropriate cues. Since the cognitive content of dreams is frequently a rather distorted version of reality, it would not be surprising if few circumstances in real life had sufficient conceptual similarity to the contents of dreams to evoke associative memories. If such memories were evoked, it is very unlikely that we would know what to make of them. For example, it is logically quite possible that *déjà vu* experiences sometimes result from similarities between current experiences and previously dreamed experiences.

Recall of dreams appears to show the same beneficial effects of repetition as recall of material learned while awake: the more frequently a dream occurs, the more likely we appear to be to recall it.

Finally, there is some scattered evidence that externally presented stimuli can intrude into and influence dreams. This means, of course, that in the most general sense external stimulation can produce conceptual learning during sleep by initiating a dream. However, the contents of the conceptual experience so elicited and the memory traces that result from it are so completely out of experimental control, that, whatever the possible theoretical significance, it would not appear to have any practical significance for learning a systematic body of conceptual material while asleep.

SUMMARY

1. Conceptual learning can be considered to have two component stages: learning concepts and learning propositions composed of familiar concepts. Each stage may be accomplished by chunking.
2. The level of acquisition increases with increased study time, especially if the study time is used to generate new encodings. Beyond the initial few seconds, rote rehearsal of a single encoding may primarily maintain the trace at the acquisition level established by that encoding.
3. Active attempts to recall appear to enhance level of acquisition more than passive reading does.
4. Level of acquisition probably has no direct effect on the rate of subsequent forgetting.
5. Higher levels of processing (such as semantic) result in a memory trace that is more highly chunked and more distinctive from other

traces; therefore it should be less subject to forgetting because of interference.

6. Speed reading is useful when you process material that you do not need to remember very long. When you want to remember material for a long time, you should take time to learn the new concepts and think about relationships between the new material and concepts and principles you already know.
7. Intent to learn is of no direct importance to learning and memory, except as it causes you to encode material in distinctive and meaningful ways.
8. Spaced learning improves both learning and retention, so if you want to remember material longer, divide your total study time for that material over several days.
9. Prior learning *(AB)* reduces the rate of acquisition for subsequent competing learning *(AC)* and produces more rapid forgetting on recall tests (proactive interference), presumably because of retrieval interference.
10. Prior learning of a competing *AB* association has no affect on recognition memory for a subsequently learned *AC* association, which indicates that there is no effect of prior *AB* learning on the forgetting rate in storage of a subsequently learned (similar) *AC* association.
11. A high level of arousal at the time of learning appears to benefit recall for that material but not recognition memory. The explanation of this effect is not yet known.
12. Simple conditioning appears to be possible during sleep, and we appear to establish some conceptual memories for the contents of our internally generated dreams. However, external stimuli are largely blocked from the higher levels of the mind, so sleep learning of externally presented material is not possible by any current means.

14 Storage: Consolidation and Forgetting

OBJECTIVES

1. To discuss the two possible functions of rehearsal: (1) maintaining the strength of memory traces during a retention interval, and (2) increasing the level of acquisition. To describe some experimental techniques for controlling rehearsal.
2. To describe the two principal hypotheses concerning unconscious consolidation of memory traces during the retention interval: (1) increasing the strength of long-term memory traces and (2) decreasing the fragility of traces to the forces of forgetting. Two versions of the increased strength hypothesis, conversion of short-term traces to long-term traces and independent consolidation of the long-term trace, will be discussed and judged unlikely to be correct. Considerable evidence will be produced to support the decreasing fragility hypothesis of consolidation.
3. To discuss the remarkably functional form of the forgetting function, which translates modest differences in degree of learning into enormous differences in how long the memory lasts.
4. To describe retrograde amnesia due to head injury, electroconvulsive shock, and drugs, and to discuss its significance for theories of memory consolidation.
5. To discuss one means by which we may know the recency of events, which derives directly from the decreasing fragility hypothesis of consolidation.
6. To describe five mechanisms of interference, several of which may produce forgetting, and to evaluate the experimental support for each mechanism.
7. To describe five lines of evidence supporting temporal decay as an important cause of loss in storage.

8. To discuss the effects on memory of sleep, time of day (circadian rhythm), and level of overall neural activity (arousal?) during the retention interval.
9. To discuss whether unconscious qualitative changes or only quantitative changes in strength and fragility occur in memory over a retention interval.

The storage phase of memory is the phase between acquisition and retrieval. Most storage processes are completely unconscious, whereas acquisition and retrieval have a substantial conscious component. The fundamental storage processes fall into two categories: the constructive processes that help preserve memory, rehearsal and consolidation, and the destructive processes, decay and interference. Rehearsal, a process of which we are consciously aware, forms a bridge between acquisition and storage. In many ways rehearsal is an acquisition process, and it was discussed from that standpoint in the previous chapter, but it also serves a trace maintenance function and is thus partly a storage process. It seems appropriate to begin this chapter with an integrated discussion of the storage and acquisition functions of rehearsal. This is followed by analysis of the principal hypotheses regarding consolidation and the evidence for and against each. Then, five possible types of interference are described along with relevant evidence. The fourth section is concerned with the evidence favoring the assumption that a process of time decay contributes to forgetting, in addition to the degradative effects of interference. Finally, we shall briefly consider whether there are qualitative as well as quantitative changes in memories during storage.

REHEARSAL

Trace Maintenance

Between the time you look up a telephone number and the time you dial it, you may rehearse the number several times. Under these conditions, rehearsal serves primarily to *maintain* the verbal short-term memory trace by periodic renewal of the trace. As long as trace strength is high enough that the probability of correct recall is 100 percent, rehearsal can obviously maintain a memory trace indefinitely. Rehearsal is especially useful when the items being remembered are relatively discrete, such as words and other verbal material. Words vary in their degree of similarity one to another but, each word has a substantially high degree of dissimilarity from every other word in our vocabulary, taking into account both phonetic and semantic attributes.

By contrast, the frequency of pure tones can be arbitrarily close to one another, reducing the degree of dissimilarity between one tone and another to some very small value. In memory for the pitch of pure tones, rehearsal is much less effective in maintaining relatively subtle distinctions between the standard and comparison tones in psychological delayed-comparison tasks. Rehearsal of tones probably introduces a substantial degree of noise into the memory trace. Rehearsal might be very helpful in remembering whether one heard a 1000 hz tone or a 200 hz tone, but is probably of little or no value in remembering whether one heard a 1000 hz tone or a 990 hz tone. The same reasoning applies to successive discrimination of things like intensities, line lengths, and angles of orientation. Supporting this hypothesis, instructions to rehearse the standard tone during a delay interval filled with an interference tone appear to produce no better retention of pitch in a delayed-comparison task than do instructions to attend to (rehearse) the interference tone.[1]

Controlling Rehearsal

In order to study other storage processes, such as consolidation, interference, and decay, it is very desirable to eliminate the trace-maintenance process provided by conscious rehearsal. This has usually been achieved by one of two methods: First, psychophysical delayed-comparison tasks can be used with sufficiently subtle distinctions between correct and incorrect comparison stimuli that rehearsal of the standard stimulus is of little or no value. Second, in verbal memory studies subjects can be given verbal tasks to perform during the retention interval that are presumed to prevent rehearsal of previously learned verbal material. For example, in a continuous recognition or recall procedure, the retention interval for any prior item is filled with many subsequent items. Since the number of items previously learned is very large and subjects are kept busy during the retention interval, it is reasonable to assume that the probability of rehearsing any prior item is negligibly small. In addition, subjects are usually given nonrehearsal instructions to further reduce the probability of rehearsing prior material during the retention interval. In the distractor memory paradigm, subjects are given only a short list to remember on each trial, such as a consonant trigram, but are required to engage in a task like rapid backward counting by threes from a three-digit number that is presumed to effectively prevent rehearsal of the consonant trigram.

One difficulty with all methods of preventing rehearsal during the retention interval by means of competing tasks is that the tasks might differ both in their capacity to prevent rehearsal and in the degree of interference with the previously established memory trace.

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[1] W. A. Wickelgren, "Associative Strength Theory of Recognition Memory for Pitch," *Journal of Mathematical Psychology*, 1966 (6), 13-61.

Acquisition

Simple maintenance of a trace is one function of rehearsal. Its second major function is to produce a higher level of initial acquisition, which causes the material to be remembered for a longer period in the absence of rehearsal. Sometimes the effect of rehearsal for the purpose of increasing the degree of learning is referred to within the two-trace theoretical framework as producing a greater degree of acquisition of the long-term trace, in addition to maintenance of the short-term trace. In either single- or dual-trace theories, the distinction is approximately the same as to whether rehearsal merely increases the strength of the memory trace up to the previously established maximum or increases the strength to an even higher level of learning. As discussed in the preceding chapter, prolonged opportunity for rehearsal of verbal material increases acquisition in much the same way as prolonging the visual or auditory presentation of the material, so long as the probability of accurate recall is close to unity. However, it may be that rehearsal of a single way of encoding the material increases level of acquisition only for the first second or two. Further increases in level of acquisition with increasing time for rehearsal may be primarily the consequence of the generation of new encodings (new ways of thinking about the material) rather than of continued rehearsal of the original encoding.

There is even more uncertainty concerning whether the visual imagery analogue of verbal rehearsal can produce comparable increases in degree of learning of pictures—for example, during blank post-exposure periods between presentation of successive pictures. Studies by Potter and Levy and Shaffer and Shiffrin indicate that the acquisition of trace strength for complex pictorial material is limited precisely to the period of visual exposure. Potter and Levy's findings suggest that earlier pictures were not processed during presentation of subsequent pictures, and Shaffer and Shiffrin's experiment indicates that increasing the blank interval following a picture exposure had no effect on subsequent recognition memory for that picture. Weaver, however, has recently found evidence for a small but significant improvement in visual recognition memory when the dark interstimulus interval was increased from two to six seconds.[2]

In view of the evidence discussed in Chapter 11, there is no doubt that visual imagery occurs. The only question concerns the degree to which this imagery can increase the strength of associations in image memory. Existing evidence suggests that there are some circumstances under which imagery may be completely ineffective in increasing trace strength, but that under other circumstances it may be helpful.

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[2] M. C. Potter and E. I. Levy, "Recognition Memory for a Rapid Sequence of Pictures." *Journal of Experimental Psychology*, 1969 (81), 10-15. W. O. Shaffer and R. M. Shiffrin, "Rehearsal and Storage of Visual Information." *Journal of Experimental Psychology*, 1972 (92), 292-96. G. E. Weaver, "Effects of Poststimulus Study Time on Recognition of Pictures." *Journal of Experimental Psychology*, 1974 (103), 799-801.

CONSOLIDATION

Like rehearsal, consolidation is a process that takes place during the retention interval and is beneficial to memory. Unlike rehearsal, consolidation is an unconscious process that is assumed to be largely beyond voluntary control. Consolidation is often assumed to proceed at the same rate regardless of any competing tasks the subject may simultaneously perform during the retention interval. The hypothesis that memory traces become more firmly fixated during the time after the end of the formal practice has been discussed ever since Müller and Pilzecher advanced their theory of perseveration and consolidation in 1900.[3]

When we confine our attention to psychological rather than to physiological mechanisms, there are two basic classes of consolidation theories. In one the strength of the trace or of some component of the trace is assumed to increase for a period following learning. In the other something besides strength changes so as to make the trace more resistant to disruption by either the normal processes of forgetting or unusual causes, such as head injury, drugs, and electroconvulsive shock. As we shall see, the evidence strongly supports the second hypothesis—that consolidation produces a decrease in the fragility of memory traces.

Increase in Strength

If over time there was a consistent increase in the accuracy of recall or recognition as the retention interval increased, the hypothesis that consolidation produces an increase in strength would be strongly supported. However, such reminiscence (absolute increases in trace strength) has only rarely been observed, and even then it is more plausibly attributed to other factors than to an actual increase in trace strength. For this hypothesis to be the least bit plausible, it is necessary to assume that two dynamically different traces mediate associative memory: a short-term trace and a long-term trace. According to this theory a rapid decay of the short-term trace occurs at the same time that consolidation produces an increase in the strength of the long-term trace. Under most circumstances, however, this produces net forgetting. Within the two-trace theory of consolidation, there are two hypotheses concerning the relationship between the short-term and long-term traces: the independence hypothesis and the conversion hypothesis.

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[3] G. E. Müller and A. Pilzecker, "Experimentelle Beitrage zur Lehre vom Gedachtniss." *Zeitschrift Psychologie Erganzungsband*, 1900 (1), 1-288.

The independence hypothesis. According to this hypothesis the short-term trace and the long-term trace are established by separate and independent mechanisms. The long-term trace requires more time to be consolidated than the short-term trace, but it decays more slowly afterwards. When Warrington and Shallice first described K. F. as possessing a normal capacity to acquire new long-term traces, but an abnormally reduced capacity to form short-term traces, the two-trace conception and the independence hypothesis of consolidation were both given a substantial boost in plausibility. However, now that K. F.'s deficit has more plausibly been attributed to a phonetic level deficiency in the representation of verbal material, there is no longer any support from this or similar cases for either the assumption of two traces or for the independence hypothesis of consolidation as an increase in strength. Furthermore, K. F. never showed reminiscence.[4] According to the independence hypothesis, reminiscence should have been observed under some conditions, since there should have been very little decay in short-term memory to mask the supposed increase in the strength of the long-term trace as a result of the consolidation process.

The conversion hypothesis. According to the conversion hypothesis, consolidation is a transfer of information from short-term to long-term memory. That is to say, while the short-term trace is available, it mediates the formation of the long-term trace. In one form or another this hypothesis has been very popular among both cognitive and physiological psychologists,[5] but to my knowledge there is no evidence supporting this position that cannot be as well or better explained by the fragility hypothesis discussed in the following section. Moreover, a number of consolidation phenomena seem impossible to account for with either the conversion or the independence hypothesis of an increase in the strength of the long-term trace.

First, virtually every relevant study using virtually any measure of trace strength shows forgetting rate to be continually slowing down with increasing trace age. Second, the susceptibility of memory traces to loss (retrograde amnesia) as a consequence of head injury, electroconvulsive shock, or drugs also appears to continually decrease with increasing trace age, and this progressive reduction appears to go on for at least several years.[6] If long-term memory is less fragile than short-term memory, and if over time an increasing percentage of the total memory trace is in long-term rather than short-term storage, then the trace as a whole should become less fragile. However, to make such a dual-trace consolidation hypothesis fit the facts, the short-term trace must be assumed to persist to a substantial extent for several years—that is, for essentially as long as the long-term trace—and such a trace could hardly be called short-term memory. Thus it would appear that the two-trace theory and the conception of consolidation as an increase in the strength of the long-term trace is simply not able to account for the basic facts.

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[4] T. Shallice and E. K. Warrington, "Independent Functioning of Verbal Memory Stores: A Neuropsychological Study." *Quarterly Journal of Experimental Psychology*, 1970 (22), 261-73. W. A. Wickelgren and K. M. Berian, "Dual-Trace Theory and the Consolidation of Long-Term Memory." *Journal of Mathematical Psychology*, 1971 (8), 404-17. E. K. Warrington and T. Shallice, "The Selective Impairment of Auditory Verbal Short-Term Memory." *Brain*, 1969 (92), 885-96. E. K. Warrington and T. Shallice, "Neuropsychological Evidence of Visual Storage in Short-Term Memory Tasks." *Quarterly Journal of Experimental Psychology*, 1972 (24), 30-40.

[5] N. C. Waugh and D. A. Norman, "Primary Memory." *Psychological Review*, 1965 (72), 89-104. R. C. Atkinson and R. M. Shiffrin, "Human Memory: A Proposed System and Its Control Processes." *Psychology of Learning and Motivation*, 1968 (2), 89-195. D. A. Norman and D. E. Rumelhart, "A System for Perception and Memory," in D. A. Norman (ed.), *Models of Human Memory*. New York: Academic Press, 1970, pp. 19-64. See Hebb, *Organization of Behavior*. R. W. Gerard, "Physiology and Psychiatry." *American Journal of Psychology*, 1949 (106), 161-73. See various papers in J. L. McGaugh and M. J. Hertz (eds.), *Memory Consolidation*. San Francisco: Albion, 1972.

Decrease in Fragility

The second class of consolidation theories is consistent with a single-trace theory of associative memory, since it assumes, not an increase in trace strength, but rather a decrease in the susceptibility of trace strength to disruption from the forces that produce normal forgetting, and from those that produce retrograde amnesia as well.

According to one version of this theory, associative memory traces have two important dynamic properties: strength and fragility.[7] Strength affects the probability of recall and recognition, but reductions in trace fragility produce less susceptibility to time decay and retrograde amnesia. Interestingly enough the theory assumes that a reduction in fragility does not affect the susceptibility of the trace to associative interference, such as that produced by learning a subsequent *AC* association on the strength of a previously learned *AB* association. According to the theory, susceptibility to interference remains constant with increasing trace age, but susceptibility to temporal decay decreases.

Temporal decay decreases as the trace ages because the trace is less fragile owing to the consolidation process. The reduction of fragility as a consequence of consolidation continues throughout the lifetime of the memory trace, which accounts for the progressive reduction in forgetting rate and susceptibility to retrograde amnesia. Consolidation is assumed to go on for years, but at a slower rate with increasing trace age. That is, the greatest rate of consolidation (the greatest reduction in trace fragility) occurs during the first few minutes following learning, and decreases progressively over the life of the memory trace. Considerable evidence supports the hypothesis that consolidation is a reduction in trace fragility.

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[6] Jost's Second Law. See C. I. Hovland, "Human Learning and Retention," in S. S. Stevens (ed.), *Handbook of Experimental Psychology*. New York: Wiley, 1951. W. A. Wickelgren, "Trace Resistance and the Decay of Long-Term Memory." *Journal of Mathematical Psychology*, 1972 (9), 418-55. L. Weiskrantz, "Experimental Studies of Amnesia," in Whitty and Zangwill *Amnesia*, pp. 1-35. W. R. Russell, *Brain, Memory, Learning*, London: Oxford, 1959.

[7] W. A. Wickelgren, "Single-Trace Fragility Theory of Memory Dynamics." *Memory and Cognition*, 1974 (2), 775-80.

Retention functions. As previously mentioned, for all types of verbal and nonverbal material the rate of forgetting appears to be continually decreasing with increasing trace age over retention intervals ranging from seconds to tens of seconds, minutes, days, months, and even years. This qualitative fact concerning forgetting rate is consistent with the fragility hypothesis. Second, mathematical formulation of this theory provides a good fit to the retention functions obtained for a wide variety of verbal and nonverbal material over retention intervals ranging from seconds to over two years.[8] For retention intervals greater than 20 seconds, the form of the function is:

$$m = Lt^{-D} e^{-It}$$

In the above equation m is the strength of the memory trace; t is the time (in seconds) following learning; L is the initial strength at the end of learning (level of acquisition); D is the time decay rate, which is inversely proportional to the rate of consolidation; $e = 2.72$ (base of natural logarithms) and I is the rate of loss from interference, which is proportional to the similarity of interpolated learning to original learning. This retention function provides a good fit to both verbal short-term memory data and to longer-lasting semantic and visual image retention as well.

When the material is encoded at an attribute level such as in phonetic short-term memory, the similarity parameter I (which represents the degree of similarity between original and interpolated material) is high. Under these conditions the retention function will be dominated by the rapid exponential decay component (e^{-It}) representing the retroactive interference process. Waugh and Norman and others have obtained evidence of the importance of retroactive interference in producing loss from verbal short-term memory. Waugh and Norman gave subjects a list of digits at rates of one digit per second and four digits per second. The list was followed by a probe digit from the list, and subjects were to recall the digit in the list that followed the probe. Recall accuracy was highest for probes from the end of the list (the most recent items) and declined the greater the delay measured in number of intervening items.[9]

Controlling for the number of interfering items, the time delay was of

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[8] Wickelgren, "Single-Trace Fragility Theory." W. A. Wickelgren, "Alcoholic Intoxication and Memory Storage Dynamics." *Memory and Cognition*, 1975, (3), 385-89.

[9] Waugh and Norman, "Primary Memory."

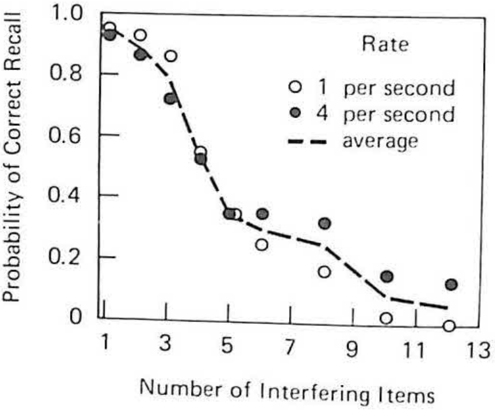

Figure 14-1. The retention function for Waugh and Norman's probe recall experiment: probability of correct recall as a function of delay measured in intervening items. (Copyright 1965 by the American Psychological Association. Reprinted by permission.)

much less significance. Figure 14-1 indicates that almost exactly the same retention function was obtained plotting recall accuracy as a function of the number of interfering items for both the slow and fast rates of presentation. However note in the figure that the one-per-second rate did produce somewhat greater acquisition and somewhat faster decay (measured as a function of intervening items) than the four-per-second rate. Thus, temporal decay does appear to play some role in short-term retention even though interference from subsequent items is the dominant factor under many conditions.

Similar results of the importance of both interference and decay have been found in short-term probe recognition memory, where subjects decide "yes" or "no" concerning whether the probe appeared in the prior list.[10] These studies also demonstrated the largely exponential form of the retention function under these conditions where interference plays a large role in producing loss of trace strength.

By contrast, when material can be encoded into semantic memory, where the similarity (I) between previously learned and subsequently learned material will be very low on the average, the retention function will be dominated by the power-function term (t^{-D}), which provides a good fit to empirical longer-term retention functions.[11] With this power-function term, the rate of forgetting will be most rapid immediately after learning but will slow down rapidly thereafter. For example, in one continuous recognition memory experiment subjects saw a word every 3.5 seconds and decided whether the word had been presented previously in the session. Delays between the original presentation of a word (acquisition) and the second presentation (retrieval test) varied from a few seconds to almost 12 minutes. The probabilities of correct recognition were converted to memory-strength measures (*d'*) using the methods of statistical decision theory, and the results are shown in Figure 14-2. If the amount of forgetting in any unit of time were simply proportional to the amount of the memory trace still present (simple exponential decay), the retention function shown in Figure 14-2 would be a straight line. Obviously it is not. The rate of forgetting is slowing down the older the memory trace. In fact, the retention function in Figure 14-2 and many other long-term retention functions studied in this manner are rather well fit by a power function of the form $m = Lt^{-D}$, which is a straight line function on a plot of log strength against log time ($\log m = \log L - D \log t$). However when the old associations are contradicted by new knowledge, the interference process can still produce rapid forgetting no matter how old the memory trace. All this would seem to be quite functional.

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[10] W. A. Wickelgren and D. A. Norman, "Strength Models and Serial Position in Short-Term Recognition Memory," *Journal of Mathematical Psychology*, 1966 (3), 316-47. W. A. Wickelgren, "Time, Interference, and Rate of Presentation in Short-Term Recognition Memory for Items," *Journal of Mathematical Psychology*, 1970 (7), 219-35.

[11] Wickelgren, "Single-Trace Fragility Theory." Wickelgren, "Alcoholic Intoxication." W. A. Wickelgren, "Trace Resistance and the Decay of Long-Term Memory," *Journal of Mathematical Psychology*, 1972 (9), 418-55.

Furthermore, when forgetting is dominated by the time decay factor alone, this retention function has a remarkable amplification property in the relationship between degree of learning and trace longevity. Specifically, for the rate of temporal decay typically observed in human memory, a difference in degree of learning on the order of a factor of two (a doubling of initial learning) would produce an increase in the useful lifetime of a memory trace on the order of a factor of 10^2, or 100. A factor of three in initial learning increases the longevity of the trace by a factor of 10^3, and so on. This permits relatively modest differences in initial learning to translate into enormous differences in how long the memory will last. Since some

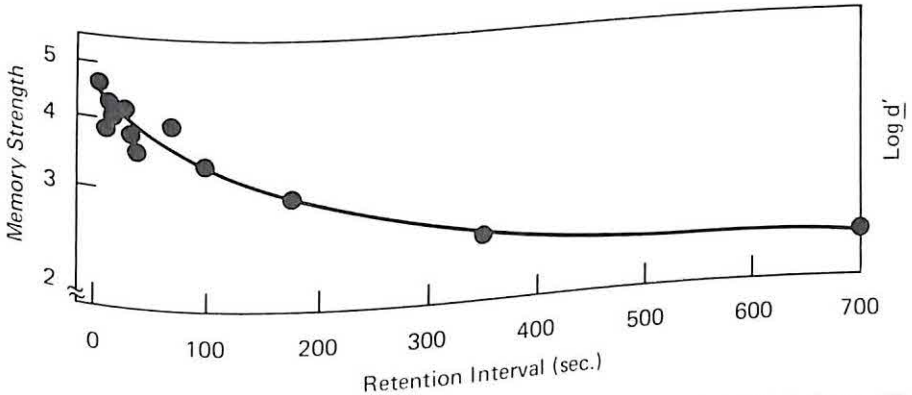

Figure 14-2. Semilog plot of memory strength as a function of time. (From Wickelgren, "Trace Resistance and Decay of Long-Term Memory.")

memories appear to last for only a few seconds or tens of seconds, while others last for years or tens of years, a factor of about 10^7, it is very functional for memory to have such an amplification property. It would be very difficult for the physiological substrate of memory to exhibit differences on the order of 10^7 in the initial strength of acquisition of the memory trace. Of course, differences in the initial degree of learning of this magnitude are trivial to obtain if one compares it to a base that can be arbitrarily close to zero strength. However, we are discussing only cases where the initial memory strength, measured at immediate retention intervals, was sufficient to produce perfect performance. Even under these conditions some traces last only for seconds, while others last for many years. Achieving a difference in initial learning strength on the order of 10^7 compared to a base strength that produces perfect performance would probably be close to impossible for the nervous system in the absence of some amplification factor.

Retrograde amnesia. Following severe head injuries that produce concussion, human beings frequently experience a loss of memory known as retrograde amnesia. Such loss can be for periods ranging from a few seconds or minutes prior to the accident up to periods of hours, days, weeks, or even years prior to the accident. The more serious the concussion, the greater the period of retrograde amnesia. As Russell noted, this appears to require the assumption of a consolidation process that extends for virtually the lifetime of the memory trace.[12] It is important to note that the consolidation process cannot be acting on the strength of memory traces, since it is not the strongest or weakest traces that are lost, but the traces most recently established, regardless of strength. Thus it appears to be necessary to assume that consolidation acts on some second parameter of the memory trace, which we here call fragility, and that concussion destroys or renders irretrievable the most fragile traces, irrespective of strength.

Occasionally retrograde amnesia from concussion is permanent, but usually the patient recovers most of the lost memories. In these cases retrograde amnesia can be considered a temporary irretrievability of memory rather than a complete destruction. Recovery from retrograde amnesia is also temporally specific—that is, the first memories recovered are the oldest memories, with the retrograde amnesia gradually shrinking toward the present.[13] Thus, the initial loss and the recovery both appear to require the assumption of a property such as fragility that is continually being reduced as a result of an ongoing consolidation process. The ability to recover from retrograde amnesia demonstrates that the disruption of the most fragile

[12] Russell, *Brain, Memory, Learning.*

[13] *Ibid.*

traces is often only temporary. Predicting the temporary or permanent character of retrograde amnesia is beyond the scope of any current consolidation hypothesis.

Electroconvulsive shock. Squire, Slater, and Chace have demonstrated that patients undergoing electroconvulsive shock treatments for mental disorders also experience retrograde amnesia that appears to be temporally specific in approximately the same manner as the retrograde amnesia produced by concussions.[14] Many experiments on animals also show that electroconvulsive shock can disrupt memory traces. These animal experiments were undertaken on the hypothesis that consolidation involved an increase in the strength of the long-term memory trace that would be completed within a period of from less than a minute to four or five hours, but the results indicated no particular time at which consolidation is complete. Various conditions, including particularly the severity of the electroconvulsive shock, can produce disruptions of memories at varying delays following original learning.[15] To my knowledge there are no studies of the effects of electroconvulsive shock on animals that demonstrate the extremely long retrograde amnesias that can be produced in human beings, but the extraordinary variability that has been observed in the period of retrograde amnesia leads one to suspect that sufficiently severe and prolonged electroconvulsive shock treatments would produce long retrograde amnesia in animals as well.

Retrograde amnesia produced by electroconvulsive shock in human beings appears to shrink over time, and there is some evidence supporting the same shrinkage in animals, though with animals there is also some contradictory evidence.[16]

Drugs. Certain drugs administered to animals at different times following learning appear to disrupt long-term retention, even though in many instances they appear to have no effect on retention immediately after their administration.[17] This has been interpolated to mean that the drugs affect the consolidation of long-term memory while not disturbing the short-term trace, which is a plausible interpretation, but the results can also be explained within the single-trace hypothesis of consolidation as a reduction in trace fragility. For example, the drugs may increase the rate of forgetting, either by increasing whatever metabolic or neural activity factors produce time decay or by reducing the rate of consolidation (here interpreted as the reduction in trace fragility). Degree of initial learning was very high in all these studies, and so an increase in the forgetting rate could have no noticeable effect shortly after learning, with the effect only appearing after substantial time had elasped, as was observed.

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[14] L. R. Squire, P. C. Slater, and P. M. Chace, "Retrograde Amnesia: Temporal Gradient in Very Long-Term Memory Following Electroconvulsive Therapy." *Science,* 1975 (187), 77-79.

[15] Weiskrantz, "Experimental Studies in Amnesia."

[16] *Ibid.*

[17] S. H. Barondes and H. D. Cohen, "Puromycin Effect on Successive Phases of Memory Storage." *Science,* 1966 (151), 594-95. B. W. Agranoff, R. E. Davis, and J. J. Brink, "Memory Fixation in the Goldfish." *Proceeding of the National Academy of Sciences,* 1965 (54), 788-93. See review by J. A. Deutsch, "The Physiological Basis of Memory." *American Review of Psychology,* 1967 (20), 85-104.

These studies also revealed no consistent time at which consolidation is complete, so the hypothesis of consolidation as a decrease in fragility is probably more consistent with these data than is the dual-trace hypothesis of consolidation as an increase in long-term memory strength.

The rate of memory consolidation may also be increased by certain drugs. McGaugh, Petrinovich, and others have found that stimulants of the central nervous system given to animals shortly *after* learning facilitated subsequent memory performance. Of course, this could also be the result of a reduction in the factors producing decay, but this seems somewhat less likely (for a stimulant) than a facilitation of consolidation. Before you rush for a cup of coffee, let me point out that these studies were done with mice and the like, and there is no guarantee of similar effects in humans. In fact, one study by Hull found caffeine to have an insignificant *retarding* effect on verbal learning. Furthermore, you must consider *all* the effects of a drug on your health and welfare, not just its effect on your memory. Lashley found that the poison strychnine facilitated maze learning in rats, but that would not lead me to take strychnine.[18]

Most studies of drug effects on human memory have not carefully determined the phase locus of the effects in acquisition, storage, or retrieval. When humans learn a list while in a mild (conscious) state of intoxication from barbiturates, nitrous oxide (laughing gas), diazepam (the tranquilizer Valium), or marijuana, memory performance on the average is inferior to memory performance after an equal amount of time spent in learning while not intoxicated.[19] The effects of barbiturates on acquisition, storage, and retrieval have not been separately determined. Nitrous oxide appears to reduce learning and also to retard forgetting of previously learned material, while diazepam, alcohol, and marijuana appear primarily to reduce the level of initial acquisition (and much of this may be because of poor attention at the time of learning).[20] There appears to be no differences from controls in the subsequent rate of consolidation or forgetting for material learned under diazepam, alcohol, and marijuana, no effect of the drugs on the storage (consolidation and forgetting) of material learned just before the drug state, and little or no effect of these drugs on memory retrieval.

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[18] See review by J. L. McGaugh and R. G. Dawson, "Modification of Memory Storage Processes." *Behavioral Science*, 1971 (16), 45-63. C. L. Hull, "The Influence of Caffeine and Other Factors on Certain Phenomena of Rote Learning." *Journal of General Psychology*, 1935 (13), 249-74. K. S. Lashley, "The Effect of Strychnine and Caffeine upon Rate of Learning." *Psychobiology*, 1917 (1), 141-70.

[19] W. O. Evans and K. E. Davis, "Dose-Response Effects of Secobarbital on Human Memory." *Psychopharmacologia*, 1969 (14), 46-61. H. Steinberg and A. Summerfield, "Influence of a Depressant Drug on Acquisition in Rote Learning. *Quarterly Journal of Experimental Psychology*, 1957 (9), 138-45. P. R. F. Clarke, P. C. Eccersley, and B. A. Frisby, "An Experimental Study of the Effects of Valium (Diazepam) on Human Memory." *British Journal of Anaesthesiology*, 1970 (42), 690-703. Wickelgren, "Alcoholic Intoxication." C. F. Darley, J. R. Tinklenberg, W. T. Roth, L. E. Hollister, and R. C. Atkinson, "Influence of Marihuana on Storage and Retrieval Processes in Memory." *Memory and Cognition*, 1973 (1), 196-200.

Even the extreme memory impairment in "alcoholic blackout" follows this pattern—namely, that memory of the events of the "night before" is poor because these events were never learned very well at the time (as measured by retention tests administered shortly after the events occurred).[21] As we saw in Chapter 12, acquisition amnesic patients can converse fairly normally and get normal scores on intelligence tests, so it is completely consistent with acquisition amnesia that someone could perform many complex cognitive tasks while drunk and later have no memory of it.

Recency judgments. The decreasing fragility of a memory trace could also serve as a kind of biological clock measuring the age of a memory trace. If fragility were a retrievable attribute, then recency judgments—how long ago one experienced an event—could be based on trace fragility. Of course many of our recency judgments, especially those for events that occurred a very long time ago, are based directly or indirectly on associations with time concepts. I remember how long ago I graduated from high school because I remember the month and year, and I know the current month and year, from which I can figure out the difference.

However, my judgment for the time elapsed since I entered my office after lunch could not be based on such associations because I have not looked at any watch or clock in the interim. Under these conditions, human beings are nevertheless able to make judgments of recency that are far beyond chance accuracy. One of the advantages of the fragility theory is that it provides an automatic mechanism for determining the recency of events for which we have established memory traces. A mathematical version of this hypothesis has been found to provide an excellent fit to human abilities to judge recencies of words presented in a continuous recognition memory paradigm where subjects had no access to clocks of any kind.[22] Interestingly enough the mediation of recency judgments via the trace fragility property should be primarily useful for intervals of less than an hour, and in this experiment subjects showed little ability to discriminate the recencies of events that occurred one hour ago as opposed to two hours ago.

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[20] A. Summerfield and H. Steinberg, "Reducing Interference in Forgetting," *Quarterly Journal of Experimental Psychology*, 1957 (9), 146-54. A. Summerfield and H. Steinberg, "Using Drugs to Alter Memory Experimentally in Man," *Neuro-Psychopharmacology*, 1958 (1), 481-83.

[21] This is a rather free translation of D. W. Goodwin, E. Othmer, J. A. Halikas, and F. Freemon, "Loss of Short-Term Memory as a Predictor of the Alcoholic Blackout," *Nature*, 1970 (227), 201-2. J. S. Tamerin, S. Weiner, R. Poppen, P. Steinglass, and J. H. Mendelson, "Alcohol and Memory: Amnesia and Short-Term Memory Function During Experimentally Induced Intoxication," *American Journal of Psychiatry*, 1971 (127), 1659-64.

The data from this time discrimination experiment also indicate that the quantity being judged by subjects is recency rather than "oldness." That is, the internal memory property used by subjects to judge recency has a high value at short retention intervals (short times) but decreases progressively at longer retention intervals, rather than having a low value immediately after acquisition that gradually increases. It is primarily for this reason that we speak of consolidation as a reduction in trace fragility rather than as an increase in trace resistance.

It should be noted that the type of biological clock provided by the fragility consolidation mechanism cannot be the same type of biological clock that permits some individuals to wake up at a particular time in the morning. This latter clock is undoubtedly tied to the daily (circadian) rhythm and not to the time delay since a particular prior event such as going to bed.

INTERFERENCE

A young child must learn hundreds of new associations every day. In light of this, why do you suppose it often takes months or years of periodic diligent practice for a child to learn the addition and multiplication tables to the point where counting on fingers and other circumlocutions are not required? Taking into account the fact that addition and multiplication are commutative ($X + Y = Y + X$ and $X \cdot Y = Y \cdot X$) and that $X + 0$, $X + 1$, $X \cdot 0$ and $X \cdot 1$ are rather easy to learn, there are less than 100 remaining associations to be learned in order to master both the addition and multiplication tables. So why should they be so difficult to learn?

The reason is interference. One is forming an association between a stimulus consisting of two digits and an operator symbol (+ or ·) and a number response. The same ten digits and the same two operator symbols appear over and over again in different compound stimuli associated to different responses. If you give a child a single addition problem, such as $5 + 8 = 13$, you can teach this association in very little time, and it will be remembered very well, so long as you do not attempt to teach a lot of other addition facts. But as soon as you begin teaching that $5 + 6 = 11$ and $9 + 8 = 17$, you are beginning to establish competing associations to each of the elements of the original compound stimulus. The formation of these associations to the same stimulus produces a variety of interfering effects on both the strength of the original association between $8 + 5$ and 13 in storage and the ability to retrieve an answer correctly using the association between $8 + 5$ and 13.

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[22] Wickelgren, "Single-Trace Fragility Theory."

The easiest sums and products, namely those involving zeros and ones, are easy because a single rule can be learned as an association to an element of the compound stimulus. For example, $X + 0 = X$, for all X. Everytime the stimulus element "+ 0" appears, this rule is triggered and yields the answer. There is little interference, since the compound stimulus element "+ 0" is not associated with any other rule for a response. (There is some interference with the "· 0" rule, because children sometimes make mistakes of the form $X \cdot 0 = X$·) In a similar manner, you have probably noted that children often rather quickly learn the answers to stimuli of the form $X + X$ or $X . X$. Once again the reason is clear in terms of reduced levels of interference. Children easily abstract the higher-level cue that the addends or the factors are identical, and this cue provides an additional differentiating stimulus element that reduces the level of interference.

The two methods—(1) abstracting additional differentiating cues from the compound stimuli and (2) learning general rules to mediate the association between the stimuli and the numerical responses—constitute the keys to learning all the rest of the addition and multiplication tables rapidly. These mnemonic methods work because they reduce interference.

The hypothesis that interference from prior and subsequent learning is a cause of forgetting is about as old as the scientific study of human learning and memory. Sometimes one hears it referred to as *the* interference theory of forgetting, but there are many different interference theories. For one thing, the hypothesis that interference plays a major role in forgetting does not preclude the possibility that other factors also produce forgetting, such as passive temporal decay (that is independent of the nature of prior or subsequent learning). There is considerable evidence to support both interference and temporal decay as contributors to storage loss. The evidence in support of interference mechanisms will be described in the present section, and the evidence supporting temporal decay will be described in the next section.

There are at least five different interference mechanisms proposed by memory theorists: competition, blocking, unlearning, response suppression, and storage load. (These five mechanisms are not mutually exclusive, so that it may be that several different interference mechanisms contribute to forgetting in associative memory.)

Competition

Do you know how to spell the five-letter word that begins with *w*, ends with *rd*, and means "mysteriously strange"? Doubtless you know that it is either *wierd* or *weird,* but if you are like me you may not be sure whether the order of the second and third letters is *ie* or *ei*. This is an example of competition, an interference factor that occurs at the time of retrieval. You have strong associations to both the *ie* form and the *ei* form from the word or concept representative that is activated in this case by giving a definition and structural information concerning the initial and terminal letters of the word. Many of us have almost equally strong associations to both spellings at the segmental (letter) level. (Incidentally, the correct spelling is *weird*—a violation of the *i*-before-*e* rule.)

The origin of such competition in the case of a "spelling demon" is obscure for most of us. Presumably we rarely see words spelled incorrectly in print. However, a substantial portion of the competition may come from our own previous misspellings of the word. Learning from one's mistakes is a very useful educational practice in the more conceptual aspects of human learning, but in the case of largely rote learning such as spelling, the educational practice advocated by Skinner and his followers (of shaping performance so as to achieve learning without errors) is highly desirable from the standpoint of minimizing competition. From this point of view it is unwise to test a child's spelling until those words have become so familiar through reading and both oral and written copying that the first test of spelling will almost certainly be without error. In a school setting the only way to insure that every child will virtually always obtain perfect spelling tests is by individualizing instruction. If all the children are given a spelling test at the same time, some children will almost inevitably make many mistakes, and these mistakes can produce memory traces that will result in substantial competition for the rest of their lives. If one wishes to be a good speller, it is very important not to see or practice the wrong spelling.

The importance of minimizing competition also applies to teaching children to write letters and numbers so as to avoid right-left mirror-image reversals of the form Ɨ, c̄, etc. Children should probably practice writing the letters and numbers properly by copying them from a model for a long time and then be gradually shaped by removing more and more segments of the model, so that they can learn to write the letters and digits without making errors. There is undoubtedly some innate difficulty with right-left reversals for human beings, especially when they are young, but it is educational folly to allow a genetically biased error tendency like to be this amplified by interfering learning.

I would rather that my children learned in an "open" educational environment where they had a considerable degree of freedom to choose what they did during the day and how rapidly they proceeded in any subject area. However, sometimes teachers who believe in educational freedom carry it to the extremes of allowing children to spell words wrong and write letters and digits backwards. In rote learning cases of this type, where similarity produces strong interference via competition between correct and incorrect alternatives, the educational advantages of minimizing competition strongly outweigh some minor restriction of human freedom. Unfortunately, people run to extremes: Some believe in rigid discipline at all times, others in laissez-faire, but most of us probably recognize that a balance must be struck. One of the applications of cognitive psychology should be to tell us where education ought to be highly structured and where we ought to allow greater individual freedom.

Competition has been studied in the laboratory setting with conventional paired-associate recall experiments by having subjects first learn an *AB* list and then an *AC* list (*AB-AC* paradigm). Subsequent to learning both lists, when subjects are asked to recall the *B* associate of *A* from the first list, they can sometimes recall both *B* and *C*, but they are not able to remember which was the correct associate for the first list and which for the second. Immediately after learning the second list, list differentiation, the ability to distinguish between the responses from the first list and those from the second, is typically quite high, over 95 percent accuracy, but a week later it may have declined to perhaps only 80 percent accuracy, not because of competition between a correct and an incorrect association with the same stimulus, but rather because of competition between associations with two highly similar compound stimuli: "*A* + first list" and "*A* + second list."[23] As long as the difference between the strength of association of the compound stimulus "*A* + first list" with the correct *B* item and the strength of association with the incorrect *C* item is high enough, competition need not markedly reduce the percentage of correct recall. However, as the associations decline in strength during the retention interval, competition may emerge as a more significant factor.

Blocking

If one has learned two different associations to highly similar stimuli (*A* and *A*′), then although one may be able to recall associates *B* and *C*, one may not be able to tell which is correct in response to *A*. This is competition at the time of retrieval. However, another possible interference mechanism that could operate at the time of retrieval is the blocking of one association by another—that is, retrieving *C* as an associate to *A* might block the recall of *B*, so that one would not even think of *B* at all.

Barnes and Underwood invented a test that logically avoids competition but is still subject to blocking. The test, called modified modified free recall (MMFR), involves allowing the subject to give two associations to the *A* stimulus following an *AB-AC* paradigm. If the recall of one associate tends to block the recall of another associate to the same stimulus, all other factors being equal one might expect a negative correlation in the recall of *B* and *C*. That is to say, the probability that a subject would recall *C* given the recall of *B* would be lower than the probability of recalling *C* given nonrecall of *B*. Martin and Greeno have examined a number of MMFR studies in search of such negative correlation and have failed to find it. There are a number of confounding factors involved in such analyses, but the present evidence certainly cannot be considered favorable to blocking as an interference mechanism.[24]

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[23] R. J. Koppenaal, "Time Changes in the Strength of *AB-AC* Lists: Spontaneous Recovery?" *Journal of Verbal Learning and Verbal Behavior*, 1963 (2), 310-19. I. M. Birnbaum, "Long-Term Retention of First-List Associations in the *AB-AC* Paradigm." *Journal of Verbal Learning and Verbal Behavior*, 1965 (4), 515-20.

If blocking is an interference factor, then supplying the *C* associates to the *A* stimulus might depress recall of the *B* associates compared to a condition in which subjects had to recall both *B* and *C* associates. Such negative effects of supplying second-list *C* associates on the recall of first-list *B* associates have been obtained, but at present the effect appears to be more plausibly attributed to the response suppression mechanism, which will be discussed in a subsequent section.[25] To my knowledge no one has determined whether supplying the first-list *B* associates would tend to block recall of the second-list *C* associates. If such an effect were obtained it would provide more definitive evidence in support of response blocking. Meanwhile blocking has not yet been definitely ruled out, but there is no compelling evidence to support the idea that it is an interference factor.

Unlearning

In 1940, Melton and Irwin proposed that, in addition to retrieval interference via competition, the subsequent learning of an *AC* pair produces a reduction in the strength of the originally learned *AB* pair. They called such a reduction of the strength of an association in storage *unlearning*.[26]

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[24] J. M. Barnes and B. J. Underwood, " 'Fate' of First-List Associations in Transfer Theory." *Journal of Experimental Psychology,* 1959 (58), 97-105. E. Martin, "Verbal Learning Theory and Independent Retrieval Phenomena." *Psychological Review,* 1971, (78), 314-32. E. Martin and J. G. Greeno, "Independence of Associations Tested: A Reply to D. L. Hintzman." *Psychological Review,* 1972 (79), 265-67. C. Wichawut and E. Martin, "Independence of *AB* and *AC* Associations in Retroaction." *Journal of Verbal Learning and Verbal Behavior,* 1971 (10), 316-21. D. L. Hintzman, "On Testing the Independence of Associations." *Psychological Review,* 1972 (79), 261-64. L. Postman and B. J. Underwood, "Critical Issues in Interference Theory." *Memory and Cognition,* 1973 (1), 19-40.

[25] See review by W. A. Wickelgren, "Memory Storage Dynamics," in W. K. Estes (ed.), *Handbook of Learning and Cognitive Processes,* Vol. 4. Potomac, Md.: Lawrence Erlbaum Associates, 1976, 321-61.

[26] A. W. Melton and J. M. Irwin, "The Influence of Degrees of Interpolated Learning on Retroactive Inhibition and the Overt Transfer of Specific Responses." *American Journal of Psychology,* 1940 (53), 175-203.

For many years there was no convincing experimental evidence in support of the unlearning hypothesis, because memory was largely tested by recall, and recall is subject to retrieval interference factors such as competition. But it has now been conclusively demonstrated that *AC* interpolated learning produces retroactive interference on recognition tests of memory for the originally learned *AB* pair.[27] Although recognition tests are not completely immune to retrieval interference factors, they can be made substantially freer of such interference at the time of retrieval than any kind of recall test. Furthermore, no plausible retrieval interference explanation has been advanced for the negative effects of subsequent learning on recognition memory for similar prior material. Thus, the unlearning hypothesis is really the only explanation available for this retroactive interference effect on recognition memory.

The principal question now is whether all unlearning is permanent. Some unlearning might merely be temporary associative suppression. Most tests of *AB* recognition memory have employed relatively short retention intervals since both *AB* and *AC* learning, so part of the storage-interference effect of the *AC* learning might be to produce a temporary suppression of the *AB* association that recovers over time. However, there have been a few demonstrations that some amount of unlearning persists for up to an hour or a day following *AC* interpolated learning, so at least some of the unlearning appears to be permanent.[28] Whether some of it is temporary associative suppression is still undetermined.

It is worth noting that unlearning requires a fairly high degree of similarity between original and interpolated learning in order to produce significant effects, since no significant retroactive interference is produced in an *AB-CD* paradigm by comparison to an *AB*-Rest paradigm.[29] (Rest is a nonlearning control group that is nevertheless prevented from prior rehearsal of the *AB* associations via some task such as reading jokes or crossing out letters in text material.) Learning other (*CD*) pairs of words unrelated to the *AB* words produces no unlearning of the *AB* association.

Recognition tests very likely tap the combined strength of association both in the forward direction from *A* to *B* and in the backward direction from *B* to *A*. Consistent with this hypothesis, unlearning can be produced in both forward and backward directions. That is, a backward unlearning design such as *AB-CB* produces approximately the same unlearning, as measured by recognition tests, as a forward unlearning design; *AB-AC*. Furthermore, when the interfering learning consists of the same stimuli and responses, but with the pairings rearranged so that both the forward and backward associations are unlearned (*AB*-*ABr* paradigm), the unlearning effect is maximal on recognition memory tests.[30]

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[27] Wickelgren, "Memory Storage Dynamics."

[28] Wickelgren, "Single-Trace Fragility Theory." J. Ceraso and A. Henderson, "Unavailability and Associative Loss in RI and PI: Second Try." *Journal of Experimental Psychology*, 1966 (72), 314-16. J. C. Abra, "Time Changes in the Strength of Extinguished Context and Specific Associations." *Journal of Experimental Psychology*, 1968 (77), 684-86.

[29] Wickelgren, "Memory Storage Dynamics."

By contrast, in MMFR recall tests it is presumed to be primarily the strength of the forward association that mediates correct performance. Consistent with this hypothesis, a greater retroactive interference is obtained with an *AB*-*AC* paradigm than with an *AB*-*CB* paradigm, nor does the *AB*-*ABr* paradigm produce greater interference than the *AB*-*AC* paradigm with the MMFR test.[31] This is as it should be, if forward associations are the primary contributor to MMFR performance.

Response Suppression

In the 1960s Postman and his associates proposed a new interference mechanism to the effect that during interpolated *AC* learning second-list *C* responses are primed by some selector mechanism, while first-list *B* responses either lose their active priming or are actively suppressed. Over a period on the order of 20 minutes or so following interpolated learning, the first-list responses spontaneously recover from their relative suppression.[32]

There are a considerable number of phenomena that support response suppression as an interference mechanism in recall (but not recognition). First, in contrast to recognition tests, significant retroactive interference effects can be found on MMFR tests in an *AB*-*CD* paradigm compared to a nonlearning Rest-control condition. Second, this retroactive interference effect is not permanent, since spontaneous recovery of the first list associates is obtained on MMFR tests, if one waits a longer time following interpolated learning. A variety of other effects are also explained by the response suppression hypothesis.[33]

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[30] Wickelgren, "Memory Storage Dynamics." J. B. McGovern, "Extinction of Associations in Four Transfer Paradigms." *Psychological Monographs*, 1964 (78), Whole No. 593.

[31] McGovern, "Extinction of Associations."

[32] L. Postman, K. Stark, and J. Fraser, "Temporal Changes in Interference." *Journal of Verbal Learning and Verbal Behavior*, 1968 (7), 672-94.

[33] Wickelgren, "Memory Storage Dynamics." McGovern, "Extinction of Associations." L. Postman and K. Stark, "Role of Response Availability in Transfer and Interference." *Journal of Experimental Psychology*, 1969 (79), 168-77. L. Postman, K. Stark, and D. Henschel, "Conditions of Recovery after Unlearning." *Journal of Experimental Psychology*, 1969 (82), (1, pt. 2). Postman, Stark, and Fraser, "Temporal Changes in Interference." Koppenaal, "Time Changes in *AB*-*AC* Lists" Ceraso and Henderson, "Unavailability and Associative Loss." N. J. Slameka, "Supplementary Report: A Search for Spontaneous Recovery of Verbal Associations." *Journal of Verbal Learning and Verbal Behavior*, 1966 (5), 205-7. A. Silverstein, "Unlearning, Spontaneous Recovery, and the Partial-Reinforcement Effect in Paired-Associate Learning." *Journal of Experimental Psychology*, 1967 (73), 15-21. R. Kammann and A. W. Melton, "Absolute Recovery of First-List Responses from Unlearning During 26 Minutes Filled with an Easy or Difficult Information-Processing Task." *Proceedings, 75th Annual Convention*, APA, 1967, pp. 63-64. H. G. Shulman and E. Martin, "Effects of Response-Set Similarity on Unlearning and Spontaneous Recovery." *Journal of Experimental Psychology*, 1970 (86), 230-35.

Storage Load

In the recent wave of research on short-term memory, some theorists began talking in terms of factors such as storage load, which referred to the number of items in a list that had to be remembered over a retention interval. To the extent that active rehearsal is involved in the short-term retention of a list of items, storage load is clearly a critical factor, since the greater the number of items the longer it will be between rehearsals of each item and the greater the opportunity for decay.

Posner and Konick, in a novel storage interference theory known as the *acid-bath hypothesis*, extended the concept of storage load to the realm of unconscious trace maintenance. The thrust of their hypothesis is that the larger the number of similar traces in storage, the greater the "acidity" of the local environment for a trace and the higher the acidity, the faster the rate of decay for a memory trace.[34] This storage-load or acid-bath theory of long-term forgetting is similar to the unlearning hypothesis in that it postulates an interfering effect on the strength of the trace in storage—that is, it is permanent like unlearning, and it is not a retrieval interference effect like response suppression, competition, and blocking. Unlearning, however, simply produces a one-time drop in the strength of the previously-stored *AB* association at the time of learning the new *AC* association; thereafter both *AB* and *AC* associations are forgotten at the same rate that they would be in isolation. By contrast, with the storage-load (acid-bath) interference mechanism, the existence of two associates to the same stimulus (*AB* and *AC*) produces a more rapid decay of each one than would be produced by a single isolated association (*AB*).

Interesting though this hypothesis is, there is not a shred of evidence to support it, and a few studies of both short-term and long-term retention have obtained results that are completely negative for it.[35] For one thing, as we previously mentioned, recognition tests show no effect of similar proactive interference on the subsequent rate of forgetting. Although there is less evidence on this matter than would be desirable, it appears that the rate of forgetting in storage of two associations to the same stimulus is the same after both have been learned, as the rate of forgetting of either association learned in isolation.[36]

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[34] M. I. Posner and A. F. Konick, "On the Role of Interference in Short-Term Retention," *Journal of Experimental Psychology*, 1966 (72), 221-31.

[35] H. L. Hawkins, V. J. Pardo, and R. D. Cox, "Proactive Interference in Short-Term Recognition: Trace Interaction or Competition?" *Journal of Experimental Psychology*, 1972 (92), 43-48.

[36] Wickelgren, "Single-Trace Fragility Theory." Postman, Stark, and Fraser, "Temporal Changes in Interference."

DECAY

In the years of research on memory that followed the classic work of Ebbinghaus, the passive decay in time of memory traces, independent of subsequent experience, was considered a possible mechanism of forgetting, until the 1920s, when Jenkins and Dallenbach published a study that demonstrated far more rapid forgetting over a period of wakefulness than during a comparably long retention interval filled with sleep.[37]

This sleep effect was interpreted as strong support of the interference theory of forgetting, because passive temporal decay was presumed to go on as rapidly during sleep as during waking. In 1932 McGeoch further assaulted the idea of passive temporal decay as a forgetting mechanism on what he called logical grounds: Nothing occurs solely as a function of time, something has to make it occur. Time does not cause anything, something else must cause forgetting.[38]

Almost everyone accepts McGeoch's philosophical position that time itself does not produce temporal decay, but rather a process or processes within the nervous system. However, the distinguishing feature of a decay process is that it is not influenced by the nature of the material learned or processed during the retention interval but depends instead upon activity of the nervous system that is relatively independent of the specific material being processed. On the other hand, it is perfectly reasonable to imagine that temporal decay may vary as a function of such factors as level of arousal, activity rhythms, and the like.

Experimental findings concerning the potency of the interference mechanism, along with McGeoch's influential paper, relegated passive temporal decay to obscurity until it was revived by Broadbent, Brown, Conrad, and others in the 1950s as a possible mechanism for forgetting in short-term memory.[39] (Interestingly enough, subsequent research rather clearly indicates that short-term memory is short term in large part because it is subject to a substantial degree of interference, and that temporal decay has a relatively small effect.) There are now five different phenomena indicating that temporal decay is an important source of forgetting in longer-term retention, particularly over retention intervals of less than a week.

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[37] J. G. Jenkins and K. M. Dallenbach, "Oblivescence During Sleep and Waking." *American Journal of Psychology*, 1924 (35), 605-12.

[38] J. A. McGeoch. "Forgetting and the Law of Disuse." *Psychological Review*, 1932 (39), 352-70.

[39] D. E. Broadbent, "Successive Responses to Simultaneous Stimuli." *Quarterly Journal of Experimental Psychology*, 1956 (8), 145-52. D. E. Broadbent, "Immediate Memory and Simultaneous Stimuli." *Quarterly Journal of Experimental Psychology*, 1957 (9), 1-11. J. Brown, "Some Tests of the Decay Theory of Immediate Memory." *Quarterly Journal of Experimental Psychology*, 1958 (10), 12-21. R. Conrad, "Decay Theory of Immediate Memory." *Nature*, 1957 (179), 4564.

Retention Functions

One line of evidence that supports the theory that both decay and interference produce memory-storage loss is the excellent quantitative fit to retention functions obtained for both verbal and nonverbal material using the fragility theory previously discussed in the consolidation section of this chapter.[40] In fitting retention functions the magnitude of the time decay parameter does not vary much for different types of material under different conditions. By contrast, the interference parameter varies enormously, as it should, since the similarity of subsequently processed material to previously learned material can vary from essentially zero to some very high value (as in *AB-AC* or *AB-ABr* paradigms).

Delay of Interference

In the consolidation section we discussed evidence derived from rate-of-forgetting and retrograde amnesia studies that the susceptibility of a memory trace to storage loss is continually decreasing with increasing trace age. If the only mechanism producing loss in storage were interference, then the shorter the delay between original and similar interfering learning, the greater the interference should be. However, studies of both recall and recognition of *AB* associations as a function of the delay between *AB* learning and subsequent *AC* interfering learning are virtually unanimous in rejecting the hypothesis that greater interference is obtained the shorter the delay between original learning and subsequent interfering learning.[41] Subsequent learning produces interference that is greater the greater the degree of similarity to original learning, so there is no doubt concerning the reality of interference as a factor producing loss in storage. At the same time, there is also no doubt that a factor that produces forgetting slows down in its effectiveness the older the trace. Experimental findings regarding delay of interfering learning clearly indicate that that force is not interference. Therefore, by exclusion, it is the susceptibility to some noninterference (decay) factor producing forgetting that is reduced as the trace becomes consolidated.

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[40] Wickelgren, "Single-Trace Fragility Theory." Wickelgren, "Alcoholic Intoxication."

[41] Wickelgren, "Single-Trace Fragility Theory." Wickelgren, "Memory Storage Dynamics." E. J. Archer and B. J. Underwood, "Retroactive Inhibition of Verbal Associations as a Multiple Function of Temporal Point of Interpolation and Degree of Interpolated Learning." *Journal of Experimental Psychology*, 1951 (42) 283-90. J. M. Newton and D. D. Wickens, "Retroactive Inhibition as a Function of the Temporal Position of Interpolated Learning." *Journal of Experimental Psychology*, 1956 (51), 149-54. J. P. Houston, "Unlearning of Specific Associations in the *AB-AC* Paradigm." *Journal of Experimental Psychology*, 1967 (74), 254-58. T. S. Howe, "Effects of Delayed Interference on List-1 Recall." *Journal of Experimental Psychology*, 1969 (80), 120-24. L. Postman and L. Warren, "Temporal Changes in Interference under Different Paradigms of Transfer." *Journal of Verbal Learning and Verbal Behavior*, 1972 (11), 120-28.

Extraexperimental Interference

There is also a negative phenomenon that supports the assumption of a time-decay process in producing forgetting. This phenomenon is the absence of evidence for what has been called *extraexperimental sources of interference*. In the 1950s and 1960s, when the interference theory of forgetting was dominant, Underwood and Postman recognized the theoretical importance of demonstrating that what produces forgetting outside the laboratory is the same interference factor that was clearly identified as important in many laboratory experiments. Accordingly, they set out to demonstrate that material with a high degree of similarity to material likely to be encountered in daily life is precisely the type of material that would be forgotten most rapidly from one day to the next.[42] Despite an enormous effort to demonstrate such extraexperimental sources, the endeavor was a complete failure. It simply does not appear that the ordinary forgetting of lists observed from one day to the next is primarily caused by interference from prior or subsequent learning outside the laboratory.[43]

It would be foolish to argue that there is *no* interference between material learned in the laboratory and material learned outside the laboratory, but the degree of similarity may be so small that this is a relatively minor cause of forgetting over the retention intervals of a day to a week that have been used to study this question. In fact, if one accepts the finding that differences in similarity to material processed outside the laboratory have no observable effect on rate of forgetting outside the lab, then one must conclude that under these circumstances interference is a very minor factor producing forgetting. One is left with the necessity of explaining what produces the large amount of forgetting over retention intervals of a day or so; by exclusion, it must be a time decay process.

According to the parameter estimates obtained from the fragility theory described previously, the relative rate parameters for the interference process and the time-decay process under extraexperimental conditions are such that virtually all of the forgetting produced over retention intervals of less than a week are a result of the time-decay factor, in the absence of an interference like *AB-AC* that is specifically designed to be of high similarity.

Sleep and Memory

The classic experiments of Jenkins and Dallenbach and van Ormer demonstrated that less was forgotten over a period filled with sleep than over a comparably long waking period.[44] This sleep effect was long interpreted to be support for interference as the sole or dominant cause of forgetting; in fact these studies of the effects of sleep on memory were probably the main reason for the decline of interest in the 1930s in decay as a mechanism of forgetting. Thus it is amusing to note that there are now three findings of the effects of sleep on memory that are inconsistent with the interference explanation of the sleep effect and that appear to require an explanation in terms of a temporal decay mechanism or a temporal consolidation mechanism or both. Since fragility theory links the gradual reduction in susceptibility to time decay directly with the consolidation process, temporal decay and consolidation are closely interlinked processes according to this theory.

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[42] B. J. Underwood and L. Postman, "Extraexperimental Sources of Interference in Forgetting." *Psychological Review,* 1960 (67), 73-95.

[43] G. Keppel, "Retroactive and Proactive Interference," in T. R. Dixon and D. L. Horton (eds.), *Verbal Behavior Theory and Its Relation to General* S-R *Theory*. Englewood Cliffs, N. J.: Prentice-Hall, 1968, pp. 172-213. G. Keppel, "Forgetting," in C. P. Duncan, L. Sechrest, and A. W. Melton (eds.), *Human Memory: Festschrift for Benton J. Underwood.* Englewood Cliffs, N. J.: Prentice-Hall, 1972, pp. 83-109.

First, Ekstrand and his colleagues demonstrated that forgetting is substantially slower over the first half of a night's sleep than over the second half. (A hypothetical illustration of the sleep effect is shown in Figure 14-3.)[45] Such an effect seems paradoxical for an interference explanation of the sleep effect. In fact, the small amount of forgetting that Jenkins and Dallenbach observed was frequently attributed to the period of wakefulness that preceded the onset of sleep. This ought to produce a greater beneficial effect of sleep over the second half than over the first half of a night's sleep, which is exactly contrary to Ekstrand's results. Even more discrepant with the interference hypothesis of the sleep effect is that the second half of the night seems to produce virtually no sleep effect whatsoever compared to an awake condition. That is, forgetting over the second half of a night of sleep is at approximately the same rate as during a comparable waking period.

The second half of sleep has a much greater frequency of dreaming than the first half, so the greater rate of forgetting might be because of interference from dreams. This appears not to be the case. Ekstrand, Sullivan, Parker, and West studied recall (MMFR) of two lists (*AB*, *AC*) over a seven-hour retention interval filled with sleep. One group was systematically deprived of dream sleep by being awakened whenever measures of eye movements, EEG (brain waves), and EMG (muscle tension) indicated the beginning of a dream. A control group was awakened the same number of times but not during dream states. There was no significant difference in retention between the control and the dream-deprived subjects.[46]

At this point it seems necessary to reinterpret the sleep effect as the effect

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[44] Jenkins and Dallenbach, "Oblivescence During Sleep." E. B. van Ormer, "Retention after Intervals of Sleep and Waking." *Archives of Psychology*, 1932 (21), 1-49.

[45] R. Yaroush, M. J. Sullivan, and B. R. Ekstrand, "The Effect of Sleep on Memory: II. Differential Effect of the First and Second Half of the Night." *Journal of Experimental Psychology*, 1971 (88), 361-66. J. F. Gann (reported in B. R. Ekstrand), "To Sleep, Perchance to Dream (About Why We Forget)," in Duncan, Sechrest, and Melton, *Human Memory*, pp. 59-82.

[46] B. R. Ekstrand, M. J. Sullivan, D. F. Parker, and J. N. West, "Spontaneous Recovery and Sleep." *Journal of Experimental Psychology*, 1971 (88), 142-44.

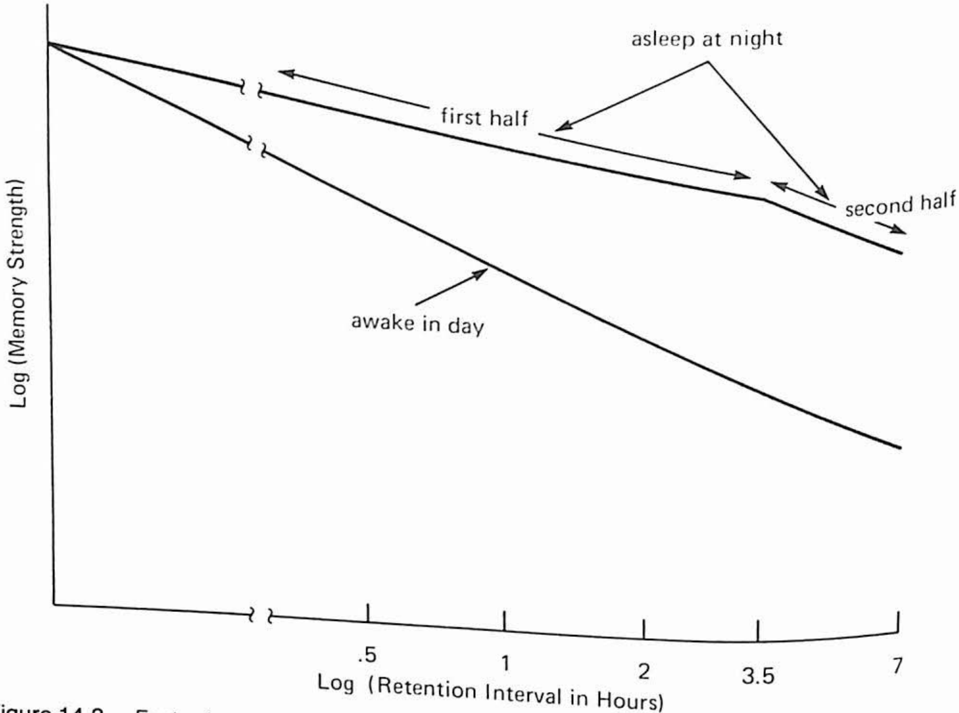

Figure 14-3. Faster forgetting over a period in the night spent asleep than during the day while awake. Note that the slower rate of forgetting at night is limited to the first half of the night, while forgetting rate in the second half is the same as during the day. (The logarithm of memory strength is plotted against the logarithm of the retention interval to make the retention functions come out as straight lines whose slope is the decay rate.)

of a general arousal or activity level of the nervous system on some spontaneous decay or consolidation process, which means that the state of the nervous system during the first half of sleep is such as to produce a less rapid rate of temporal decay or a faster rate of consolidation than occurs at the higher state of neural arousal characteristic of the second half of sleep or during the time an individual is awake.

Hockey, Davies, and Gray obtained evidence that it is not sleep per se that retards forgetting, but rather the time of day normally occupied by sleep in a person's day-night cycle (period of time in the circadian rhythm). They measured recall after five hours of sleeping or waking during either the night or morning, keeping some subjects awake during their normal nightly sleeping period and other subjects asleep during a five-hour period when they were normally awake. They also tested the usual groups for retention after a period of sleeping at night and after a waking retention interval during the morning. They found that recall after a five-hour retention interval at night was superior to recall after a five-hour retention interval during the day, irrespective of whether subjects were awake or asleep during the retention interval! (There was a very slight difference in favor of the sleeping as opposed to the waking condition, but it was considerably smaller than the time-of-day effect.)[47] This result needs replication, but it is certainly consistent with the previously discussed differences between the first and second half of the night. Once again, the sleep effect appears to be a reduction of decay or an increase in consolidation that depends on arousal or other nervous-system rhythms. An interference explanation of the "time of day" effect would appear to be impossible.

As Ekstrand pointed out, studies in three different laboratories have demonstrated that the point of interpolation of sleep makes a considerable difference in the magnitude of the sleep effect. Specifically, if after learning, eight hours of sleep occur immediately followed by 16 hours of wakefulness, retention is far better than if 16 hours of wakefulness are followed by eight hours of sleep. This means that you not only will remember very well on the morning of the exam the material that you crammed-in the night before, you will also remember it far better later on than material you learned earlier in the day. (Of course all other factors are not equal: attempting to cram the learning of a large amount of material into a small period of time usually produces an inadequate degree of understanding that raises the average similarity value of the learned material to subsequently processed material, which produces more rapid forgetting. However, the sleep effect is undoubtedly one reason why cramming the night before is not absolutely disastrous.)

This finding that the occurrence of sleep early in the retention interval produces superior retention to that obtained if the same amount of sleep occurs later in the retention interval is in sharp contrast to the results obtained with retroactive interference. As previously discussed, the delay between original and similar interfering learning has no effect on the magnitude of interference, whereas the delay between original learning and sleep plays a substantial role in retention. Once again it appears impossible to explain the sleep effect in terms of a reduction of interference.

Furthermore, as illustrated in Figure 14-4, the effects of point of interpolation of sleep are precisely as predicted by the two-factor fragility theory of memory storage dynamics, according to which the decreasing fragility of the trace (decreasing because of the consolidation process) affects the rate of time decay but not the susceptibility to interference. As we have seen, the sleep effect must be attributed either to an increase in the rate of consolidation or to a reduction in the force of temporal decay. According to fragility theory, either an increase in the rate of consolidation or a reduction in the force of temporal decay will be most effective immediately following learn-

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[47] G. R. J. Hockey, S. Davies, and M. M. Gray, "Forgetting as a Function of Sleep at Different Times of Day." *Quarterly Journal of Experimental Psychology,* 1972 (24), 386-93.

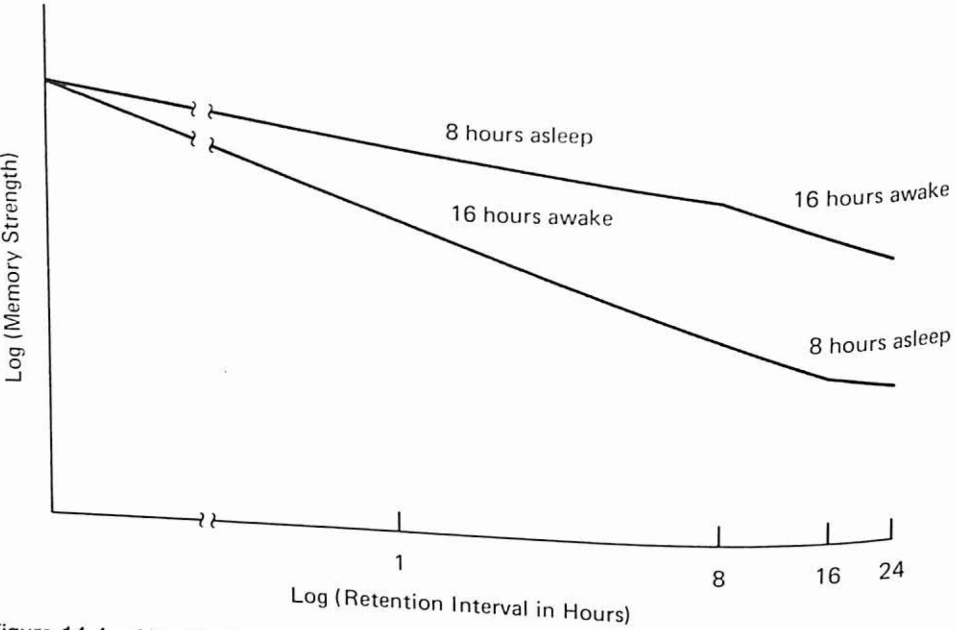

Figure 14-4. Hypothetical retention functions illustrating the point of interpolation findings for the sleep effect that eight hours of sleep immediately following learning followed by 16 hours awake produces superior retention to 16 hours awake followed by eight hours asleep. Since long-term retention functions are linear on this log-log scale, it is graphically clear that this is a prediction-of-fragility theory.

ing, when the trace is most fragile. This combination of the decay and consolidation explanations of the sleep effect is almost precisely the sort of combination envisioned by Ekstrand in 1972 in his seminal review of the effects of sleep on memory.[48]

Neural Activity and Memory

Though far from conclusive, some support for a decay process in memory comes from studies of forgetting as a function of the level of neural and/or metabolic activity during the retention interval. Decreases in temperature generally slow down biological activity. Alloway found less forgetting of a T maze habit in the grain beetle when the beetles were kept in a cold environment during the retention interval. Rensch and Dücker found less forgetting in fish given a tranquilizing drug or kept in darkness during the retention interval. French found an increase in forgetting in fish that were heated during the retention interval. Gleitman and Rozin replicated this result in one study, but they failed to find the same effect in another study.[49] As mentioned earlier in the chapter, light nitrous oxide (laughing gas) anesthesia reduces the forgetting rate for previously learned verbal material in human beings.

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[48] Ekstrand, "To Sleep, Perchance to Dream."

ARE THERE QUALITATIVE CHANGES IN MEMORY?

Throughout this chapter we have discussed consolidation and forgetting as if these processes involved only quantitative changes in memory traces. The assumption that memory traces do not unconsciously evolve in any qualitative way without new learning has been either an explicit or implicit assumption of virtually all memory researchers. However, there have been a few voices to the contrary, such as some Gestalt psychologists who studied memory for form and the famous English psychologist Sir Frederic Bartlett, who studied memory for stories.

Wulf and other Gestalt psychologists noted that if subjects were given "bad" figures, such as squares or circles with gaps (holes) in them, over time subjects would tend to fill in the gaps, so as to form "good"— complete—figures. Hebb and Foord, using recognition memory tests obtained evidence that contradicted this qualitative change hypothesis. They claimed that their study was less subject to response bias effects than the earlier recall studies of the Gestalt psychologists. Subsequent recognition studies have obtained a variety of results, including some that show positive evidence for the Gestalt prediction of qualitative changes.[50]

Bartlett showed that the recall of folk tales taken from different cultures will tend over time to have elements that are more familiar in terms of the

[49] H. Gleitman, "Forgetting of Long-Term Memories in Animals," in W. K. Honig and P. H. R. James (eds.), *Animal Memory*. New York: Academic Press, 1971, pp. 1-44. T. M. Alloway, "Effects of Low Temperature upon Acquisition and Retention in the Grain Beetle (Tenebrio Molitor)." *Journal of Comparative and Physiological Psychology*, 1969 (69), 1-8. B. Rensch and G. Dücker, "Verzögerung des Vergessens erlernter visuellen Aufgaben bei Tieren durch Chlorpromazin." *Pfluegers Archiv fuer die Gesamte Physiologie des Menschen und der Tiere*, 1966 (289), 200-214. Dücker and B. Rensch, "Verzögerung des Vergessens erlernter visuellen Aufgaben bei Fischen durch Dunkelhaltung." *Pfluegers Archiv fuer die Gesamte Physiologie des Menschen und der Tiere*, 1968 (301), 1-6. J. W. French, "The Effects of Temperature on the Retention of a Maze Habit in Fish." *Journal of Experimental Psychology*, 1942 (31), 79-87.

[50] F. Wulf, "Uber die Veranderung von Vorstellungen," *Psychologishes Forschung*, 1922 (1), 333-73. See review by D. A. Riley, "Memory for Form," in L. Postman (ed.), *Psychology in the Making*. New York: Knopf, 1962. D. O. Hebb and E. N. Foord, "Errors in Visual Recognition and the Nature of the Trace." *Journal of Experimental Psychology*, 1945 (35), 335-48. A. D. Baddeley, "Closure and Response Bias in Short-Term Memory for Form." *British Journal of Psychology*, 1968 (59), 139-45. D. Donderi, B. Case, L. Rossoff, and J. Willis, "Change in Visual Memory Following Discrimination Learning." *Canadian Journal of Psychology*, 1970 (24), 401-16. T. C. Daniel, "Nature of the Effect of Verbal Labelling on Recognition Memory for Form." *Journal of Experimental Psychology*, 1972 (96), 152-57.

culture of the person doing the recalling. Here again subsequent experiments have not always supported the qualitative change hypothesis.[51]

In both memory for form and memory for stories, it is relatively useless to argue that such effects cannot be obtained. However, such qualitative changes in recall or recognition are easily explainable on the basis of purely quantitative changes in memory traces. For example, if someone remembers a form in part by using the verbal code *circle with a gap*, a more rapid forgetting of the gap information will produce the apparently "qualitative" change. In memory for stories, more rapid forgetting of some kinds of information will also produce recall of stories that differ in apparently "qualitative" ways from the originals. There is no evidence against qualitative change in memory, but there is also no evidence for it, and there is still no reason to doubt the parsimonious hypothesis that only quantitative changes occur in memory storage in the absence of new learning or rehearsal. Furthermore, there is no reason to doubt the parsimonious hypothesis that changes in trace strength are strictly negative, that at the level of trace storage there is only forgetting, never reminiscence (although because of consolidation the rate of decay is continually decreasing the older the memory). So far as we know, time does not "rewrite the lines" in our memories, it only makes what is written on some lines fade or get smudged faster than what is written on other lines (if you will pardon this rather poor nonassociative analogy to our associative memories).

SUMMARY

1. The primary function of rehearsal is trace maintenance during a retention interval. Increased trace acquisition is possibly a secondary function of rehearsal, but rehearsal of a single encoding may increase acquisition level only for the first second or two; further increases in acquisition result from new encodings.
2. Consolidation is not an increase in trace strength, but a reduction in trace fragility. Reduction in trace fragility is most rapid immediately after acquisition, but consolidation apparently continues at a progressively decreasing rate for the entire lifetime of a memory.
3. The form of the retention function is such as to translate moderate differences in level of acquisition into large differences in longevity of retention.

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[51] F. C. Bartlett, *Remembering: A Study in Experimental and Social Psychology*. Cambridge: Cambridge University Press, 1932. R. M. Dawes, "Memory and Distortion of Meaningful Written Material." *British Journal of Psychology*, 1966 (57), 77-86. A. Gauld and G. M. Stephenson, "Some Experiments Relating to Bartlett's Theory of Remembering." *British Journal of Psychology*, 1967 (58), 39-49. See review by O. L. Zangwill, "Remembering Revisited." *Quarterly Journal of Experimental Psychology*, 1972 (24), 123-38.

4. Retrograde amnesia appears to be temporally selective, in that the memories most likely to be lost are those most recently established, independent of strength. The same temporal selectivity applies to recovery from retrograde amnesia: the first memories to return tend to be the oldest memories, not the strongest or the weakest.
5. Nonassociative recency judgments of events occurring within the last hour may be based on the fragility (degree of consolidation) of the memory traces for these events. The results of the consolidation process may thus provide a kind of intermediate-term biological clock, time tagging events for recency.
6. Associative interference is the strengthening of at least two associations to the same node (*AB* and *AC*). Interference can operate during acquisition, storage, or retrieval.
7. Retroactive associative interference (*AC*) has a negative effect on memory for the previously learned association in three ways: (1) The *AC* association competes with the *AB* association at the time of retrieval in a recall test (retrieval interference). (2) The learning of the subsequent *AC* association reduces the strength in storage of a prior *AB* association (unlearning or storage interference). (3) The learning of the *C* response may temporarily reduce the subject's set to produce the *B* response to any stimulus in a recall test.
8. Proactive associative interference (*AB*) (1) often has a negative effect on the learning of a subsequent (*AC*) association (acquisition interference or negative transfer), and (2) produces competition on a delayed recall test for the subsequent association (retrieval interference), but it probably has no direct effect on the loss of trace strength for the subsequent association in storage (no acid-bath storage interference).
9. Unlearning of a prior association occurs at the time of learning the subsequent interfering association and not afterwards in the storage of both associations. In the absence of rehearsal, there are no negative effects of storage load on forgetting rates.
10. Two factors produce loss of trace strength in storage: temporal decay and interference.
11. Temporal decay is the forgetting factor that slows down owing to decreasing trace fragility with increasing trace age. The susceptibility of an *AB* association to storage interference (unlearning) that results from learning an *AC* association remains constant regardless of trace age and consolidation.
12. Forgetting occurs more slowly during the time of day in which one usually sleeps than during times when the brain operates at a higher level of general activity (arousal). The beneficial effects of sleep on retention are largely or entirely time-of-day effects and have little to

do with the reduction of opportunity for interference. The sleep effect on retention may be the result either of a reduction in the general neural activity factors producing temporal decay or possibly of an increase in rate of consolidation during sleep.

13. Apparently qualitative changes in recall can occur over increasing retention intervals, but such qualitative changes in output might result from purely quantitative changes in the strengths of memory traces, because of forgetting traces at different rates.

15

Retrieval: Recall and Recognition

OBJECTIVES

1. To distinguish elementary retrieval tasks from more complex retrieval tasks.
2. To discuss the relation between perceptual recognition and recognition memory.
3. To make the point that even item-recognition memory must be considered a type of associative recognition memory, that the familiarity of an item is based on the strength of some association.
4. To describe a two-stage model of recall and recognition: a memory retrieval process followed by a decision process.
5. To discuss the decision processes for several different recognition and recall tasks and the measurement of memory strengths in these tasks.
6. To compare the direct-access and search hypotheses of memory retrieval and to present the evidence favoring a direct-access process for both recognition and recall.
7. To discuss whether recognition is better (easier) than recall.
8. To compare the storage, retrieval, and decision aspects of recognition and recall.
9. To explore conditions such as fugue amnesia, multiple personality, dreams, hypnotic trance, and the drug state where retrieval may vary with the global state of the mind.
10. To describe factors at the time of retrieval that can affect recall performance such as the time available for retrieval, arousal, motivation, attention, number of relevant and irrelevant cues, and the tendency to make inferences from fragmentary recall.

You have surely had the experience of failing to *recall* the name of someone you know rather well. It is an embarrassing, but all too common experience. Usually you would recognize the name immediately if you heard it, and often you can later recall the name, given more time, new cues, and less anxiety. This memory problem is not primarily one of acquisition or storage. The trace for the name is in your memory, you just cannot retrieve it at the moment.

It is even more disorienting to meet someone you are certain you know (and who comes over and starts talking to you like an old friend), but about whom you cannot recall a single fact. Usually these are people you met in a very different context from the one you are in at present, and apparently the context is an extremely important cue in these cases for retrieval of information about the person. Here also the primary problem is likely to be one of retrieval. At least some memories about the person are doubtless present somewhere in your mind, if only you could get to them.

The retrieval process in *recognition* memory can also be unreliable, as illustrated by the *déjà vu* experience. In *déjà vu* one feels in the middle of a situation that what is happening has all happened before, even though one knows full well, on other grounds, that this could not possibly be so. This strong feeling of false familiarity occurs for places and, more strikingly, for events. In some types of neurological disorders *déjà vu* experiences occur in a particularly strong and frequent form, but most normal people have also experienced *déjà vu*. One plausible explanation for normal *déjà vu* is that the events that trigger the *déjà vu* experience are similar to some previously stored event (or dream) even though there are enough distinguishing characteristics to convince one that the event has actually not occurred before.

ELEMENTARY AND COMPLEX RETRIEVAL TASKS

Retrieval is the process by which we use our memories to *recognize* something as familiar, *recall* something we previously learned, or judge the *recency* of some event experienced in the last hour. Among the three Rs of retrieval, recency has received comparatively little systematic attention and is not established as a basically different type of retrieval on a par with recognition and recall; hence we shall not discuss the retrieval of recency information here. Nor shall we concentrate on the more complex memory retrieval processes that frequently occur in our daily lives and that have sometimes been studied in the laboratory; instead we shall confine our attention to elementary recognition and recall.

Recognition can be subdivided into yes-no and multiple-choice recognition. A *yes-no recognition memory* task is one in which the subject is given a small amount of material and required to make a single mental decision regarding whether that material was presented before. Subjectively, this decision is based on the strength of the overall feeling of familiarity for the material. A *multiple-choice recognition memory* task is one in which several alternatives are presented and the subject chooses the one that was presented before. Multiple-choice recognition appears to be based on the comparative familiarity of each alternative. An elementary *recall* task is one in which a subject reports the first thought that comes to mind following attention to some cue(s).

Complex retrieval tasks presumably involve a sequence of elementary recognition and recall processes. Ordinary memory retrieval frequently involves a complex sequence of recognition and recall judgments. For example, in trying to recall someone's name, I first attempt to generate it directly from my concept or image of the person. If that fails, I try to recall specific information concerning the person in an attempt to provide additional retrieval cues to increase the probability of recall from associative memory. In the process a number of alternative names usually pop into my mind, and these are tested for correctness via recognition memory. Finally, I have sometimes resorted to going through the alphabet generating common first names—A-names, then B-names, and so forth—testing each recalled name by recognition memory.

It is difficult to control an experimental recognition or recall task so as to insure that it is confined to a single elementary recognition or recall process, and most experimental tasks probably fall short of the ideal. Nevertheless it seems worthwhile to keep the ideal definition in mind and to concentrate on studies that appear closest to achieving the ideal of studying the two elementary retrieval modes of recognition and recall.

It is generally good scientific strategy to break a complex process into parts and study the more elementary components in isolation. For example, the *free-recall* paradigm begins with a list of perhaps 20 words, followed by an instruction to the subject to recall as many of the words on the list as possible. Free recall is a complex process: repeated recall is required, and subjects can, and probably do, check their generated responses via recognition memory. Most important, the cues the subject uses to recall each member of the list are not under experimental control. In free-recall situations, retrieval strategies differ enormously, and this makes precise analysis of the process difficult if not impossible. It is often argued that free-recall situations are useful to study because they are similar to the more complex recall tasks that occur in real life. However, one of the principal advantages of scientific experimentation is that processes can be studied in the laboratory under much more carefully controlled conditions than occur in real life. Free-recall tasks simply fail to take sufficient advantage of the capacity for careful control. In analyzing recall we shall concentrate on studies of *probe recall*, where subjects produce a single response to a specific cue, as in a paired-associate recall paradigm.

Examples of complex recognition tasks are somewhat more difficult to obtain. Of course a multiple-choice recognition task is more complex than a yes-no recognition task; furthermore, the complexity of multiple-choice recognition obviously increases with an increasing number of alternatives for the subject to consider. Complexity can also be introduced into a simple yes-no recognition task, if subjects can enhance their recognition of an item or pair by recalling some mnemonic that they used at the time of acquisition. For example, a subject may have learned the pair *B-eggs* by learning the mediated association *B-bacon-eggs*. In principle, it might be possible to study such examples of recall-mediated recognition separately from elementary recognition by strict control of the time permitted the subject to make a recognition decision. However, recall can be very rapid, and there are no studies available today that allow us to distinguish between elementary recognition memory and recall-mediated recognition memory.

Similarily, many studies of paired-associate recall do not restrict the time for recall sufficiently to prevent subjects from using a recognition check on the first thought that pops into their mind following presentation of the stimulus. We know so little concerning the temporal dynamics of either the recall or the recognition retrieval processes that we do not know how little time must be allotted to recall in order to exclude recognition checking. Thus, many of the elementary recognition and recall tests we discuss in this chapter are probably not so elementary as we might desire, but we can at least exclude obviously complex retrieval tasks from primary consideration.

PERCEPTUAL RECOGNITION AND RECOGNITION MEMORY

Please pronounce the following list of consonant-vowel-consonant (CVC) syllables as rapidly as possible: GIP, FIP, MIP, SIP, KIP, WIP. Now without looking back, cover the list of CVC syllables and answer the following questions: Were any of the CVC syllables words? If so, which one(s)? Did you recognize some CVC syllable as a word at the time you read it or only subsequently, after using your phonetic short-term memory? Many people fail to recognize a word such as SIP when it is embedded in a set of nonsense syllables. This demonstrates that it is possible to perceive and pronounce a word at some phonetic level without recognizing that it is a word and getting the associated feeling of familiarity. The same word "recognition" is often used to describe both perceptual recognition and recognition memory. However, there is at least some sense in which one can perceive a whole stimulus (presumably you pronounced each CVC syllable as a single integrated verbal unit, not as a sequence of letter names) without recognizing it in the sense of retrieving its familiarity in memory as a unit.

Of course, what you perceived in the above case was presumably not an integrated word unit but a syllable unit or a set of phoneme (letter sound) units. Presumably you had a feeling of familiarity for the letter constituents of each CVC syllable, and this feeling may have been completely coincident with your perceptual recognition of each syllable. Had you received a sequence of stimuli such as GLAP, PLAP, TLAP, you might have recognized immediately upon perceiving TLAP that it contains an unfamiliar phoneme transition *TL*. Had you activated the chunk representative for SIP at the word or concept level you might well have simultaneously retrieved its familiarity value.

The relationship between the perception of a stimulus and the retrieval of a feeling of familiarity for that stimulus—that is, between perception and recognition memory—is still a mystery. When the same word appears in an associative memory on different occasions and signals the same concept, it should activate the same internal representative in memory. There may be some degree of independence, or some time delay, between the time the stimulus activates its appropriate internal representation (perception) and the growth of a feeling of familiarity for that stimulus (recognition memory). However, it is at least as plausible to assume that these two processes occur at precisely the same time in a manner that is so totally interdependent that the processes cannot and should not be distinguished. At present we simply do not know how these two processes interact.

ITEM MEMORY AND ASSOCIATIVE MEMORY

Asking subjects whether they have ever been exposed to an item before is a relatively pure example of what might be called recognition memory for a single item. By contrast, when subjects are asked whether two familiar words were presented previously as a pair in a paired-associate learning task, the question refers not to the familiarity of the individual words but to their pairing, in which case the decision is presumably based on the strength of association between the two words, which may be indirectly mediated by the strength of associations from each word to some higher-level proposition or image of which these two words are constituents.

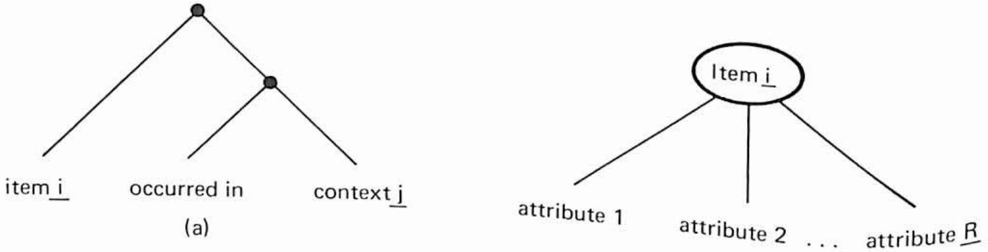
Most so-called item-recognition tests involve presenting a list of words followed by a recognition test in which the presented words are mixed with a number of distractors, and subjects have to decide whether each word was presented in the preceding list. Under these conditions, the decision is not whether any word is absolutely familiar, because each word has generally been experienced tens of thousands of times in the subject's lifetime and therefore is familiar on an absolute basis. The question concerns some type of association between each word and the experimental context. Thus, such relative item-recognition memory tests are actually special cases of associative recognition memory tests.

Furthermore, even the supposedly absolute recognition memory tests for completely novel stimuli may well tap the strength of association between the familiar constituents of the novel stimulus and some higher-level chunk node created to represent the entire set. Since this is very likely the way in which many word-word paired associates are learned, precisely the same type of associative strength may constitute the familiarity dimension judged in all cases of recognition memory. There is really no need to assume two types of strength, item strength and associative strength. Associative strength alone would appear to be sufficient. It is sometimes convenient to talk about item strength in the context of "item" recognition memory tests. There is no harm in this, so long as it is understood that "item" strength probably refers either (1) to the strength of association between an item node and a node representing the context or (2) to the intra-item associative strength (associations of the attributes of the item to each other or to their chunk node). A diagram representing an associative coding of item memory is shown in Figure 15-1.

Throughout this chapter we shall discuss memory retrieval using examples from either paired-associate or item-recognition memory more or less interchangeably. So far as we can now determine, item memory is a kind of associative memory, so there is little reason to distinguish between them.

TWO MEMORY OUTPUT STAGES: RETRIEVAL AND DECISION

There are two stages in output from memory: (1) the *retrieval* of relevant memory traces, and (2) a *decision* as to what response to make based on the traces retrieved. The retrieval process is assumed to operate on memory storage using the retrieval cues (stimuli) as input to retrieve (access) the relevant memory traces. In the strength formulation, what is retrieved are the strengths of one or more memory traces, which then become input to a decision process that selects a response. The response is "yes" or "no" on a



(a)
Relative (Context-Dependent)
Item Memory

(b)
Absolute (Context-Free)
Item Memory

Figure 15-1. Two associative interpretations of item memory. In (a), the meaning of item memory is that item *i* has been associated to context *j*, possibly by means of a proposition such as "item *i* occurred in context *j*." In (b), the meaning of item memory is that a chunk node has been formed for the attributes of item *i* at some time in the past.

yes-no recognition test, or one of several responses on a recall or multiple-choice recognition test.

Let's consider *AB* paired-associate memory as an example. In the usual forward recall test, the retrieval cue is stimulus item *A*. This initiates retrieval of the memory traces to item *A*. When the *AB* association is in storage and when the recall retrieval process retrieves the *AB* memory trace as the only trace retrieved or as the trace with the greatest strength, the decision process selects and outputs *B* as the response. It is reasonable to assume that the decision rule used by the recall decision process is to output the response that has the greatest retrieved strength of association with the stimulus (retrieval cue). Perhaps there is also a recall threshold such that no response is emitted, unless an association with *A* has a strength greater than some threshold level. A pure *threshold decision rule* is that a response is emitted if and only if its strength of association with *A* exceeds the threshold. If more than one associative strength exceeds the threshold but only one response is permitted, subjects might then also employ a *maximum decision rule* and select the alternative with the greatest strength.

Obviously recall can be aided by introducing additional *retrieval cues*. For example, in paired-associate recall, if one supplies not only the stimulus word but also the first letter of the response word, the probability of correct recall will increase. Besides such structural retrieval cues, one can also provide a synonym or a strong associate of the response word as a retrieval cue. All these cues will increase the probability of correct recall. This is perfectly reasonable under the assumption that the strengths of association from various cues add in some way, increasing the probability that the strength of the correct alternative will exceed the threshold.

In paired-associate recognition memory the retrieval cues for the *AB* association consist of both the *A* and *B* items of the pair. The recognition retrieval process takes these retrieval cues as input and produces the strength of association between *A* and *B* as output. This strength serves as the input to the decision process, which may then follow the *criterion decision rule:* respond "yes" (the pair is familiar) if the retrieved strength of the *AB* association (its familiarity) exceeds some criterion; respond "no" if the retrieved strength is less than the criterion. A recognition criterion differs from a recall threshold in one respect: the recognition criterion is assumed to be highly variable depending on the subject's bias to say yes, whereas the recall threshold is typically considered to be a constant, high level of strength of the *AB* association below which one simply cannot think of (retrieve) the *B* response to the *A* stimulus.

DECISION RULES AND STRENGTH MEASUREMENT

Yes-No Recognition: Criterion Rule

The most plausible hypothesis about the decision stage of recognition memory is the *criterion rule*, whereby strength (familiarity) is compared to a criterion. If memory strength is above the criterion, the subject responds "yes" (the pair is old or familiar); if it lies below the criterion, the subject responds "no" (the pair is new or unfamiliar). Even under constant conditions there is assumed to be substantial variability in the amount of memory strength acquired by pairs during learning, and there might be variation at the time of retrieval as well. It is also possible that there is variation in the storage phase as a result of different rates of consolidation, decay, or interference for previously presented (old) items. Furthermore, there is variation in the strength of new pairs owing to their similarity or association to old items and to noise in the retrieval process. This all produces a distribution in the memory strength for both old and new items, as illustrated in Figure 15-2.

A rather elegant way to measure the strength of the memory trace for old items under any condition is provided by statistical decision theory, a theory introduced into psychology by Thurstone and greatly extended by

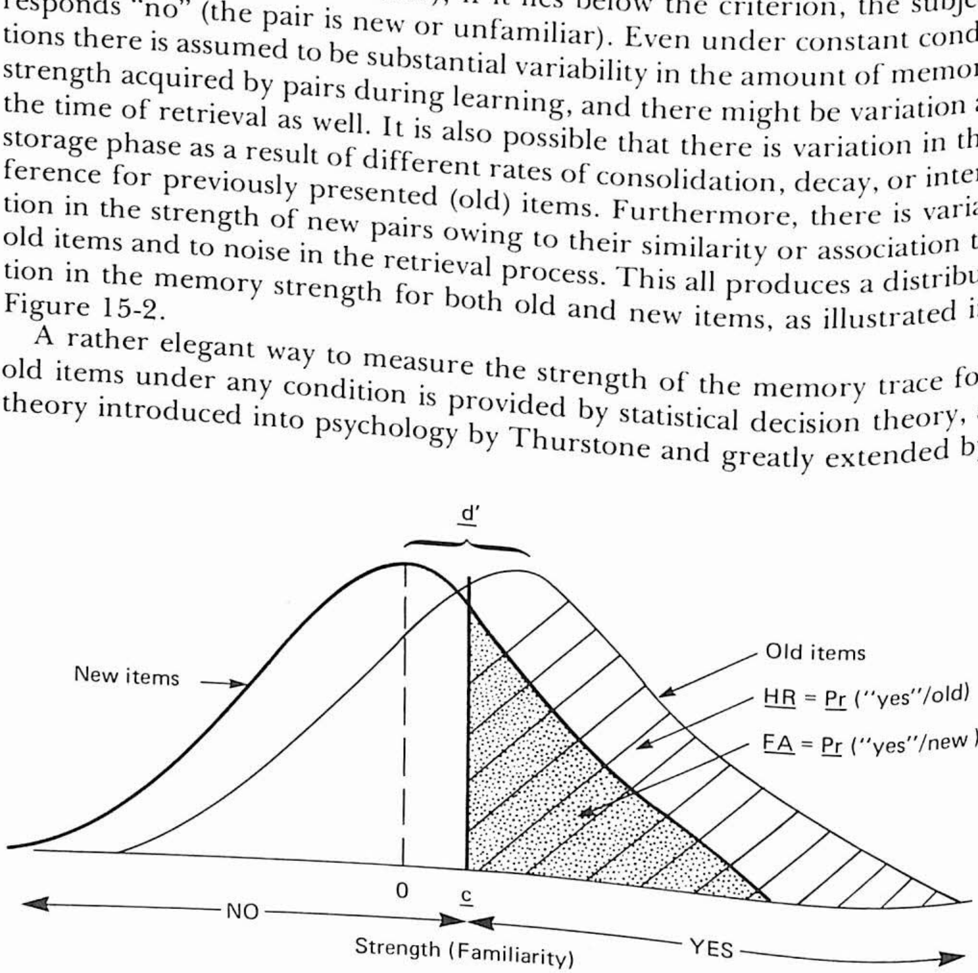


Figure 15-2. Hypothetical strength distribution for old and new items. According to the criterion decision rule, whenever the strength of an item is above the criterion (c), the subject responds "yes," and whenever the strength is below the criterion, the subject responds "no." The hit rate, *HR*, is the probability of correctly recognizing an old item. The false-alarm rate, *FA*, is the probability of incorrectly recognizing a new item. From the hit and false-alarm rates, *d'* can be calculated, which is the difference in the average memory strength of the old and new items measured in units of the standard deviation of the distributions (here assumed to be equal for old and new items).

Tanner, Swets, and Green. The methods and application of statistical decision theory to memory are discussed in detail elsewhere and are beyond the scope of this book.[1] What the statistical decision analysis of recognition memory does is convert the empirical probabilities of correct and false recognition (hit rate and false-alarm rate) into a measure of the strength of the memory trace for the old pairs. This measure of memory strength (often given the symbol d') takes the average strength of new pairs to be the zero point on the strength scale, and the standard deviation of the strength distribution for new pairs is the unit of measurement. The strength measure d' is thus an *interval scale*—that is, a scale that measures the difference in strength of correct and incorrect pairs, rather than absolute strength.

One of the primary successes of the statistical decision analysis of yes-no recognition memory is that it provides a plausible solution to the problem of differences in criterion across subjects and across different conditions for the same subject. That is to say, both correct and false recognition rates will increase, the lower the subject places his or her criterion on the strength scale. It is desirable to obtain a measure of recognition memory accuracy (strength) that is independent of criterion placement. Such a measure is provided by the d' score, since the same d' value will be obtained using the methods of statistical decision theory regardless of where the subject places his or her criterion on the strength scale.

Multiple-Choice Recognition: Maximum Rule

The statistical decision analysis of recognition memory can be extended to multiple-choice recognition rather plausibly by means of the *maximum rule* as suggested by Thurstone, according to which the subject chooses the alternative that has the maximum strength or familiarity.[2] Tables exist that translate from the probability of correct choice for various numbers of alternatives to the measure of d', using simplifying assumptions such as the equality of the standard deviations of all of the strength distributions for each alternative.

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[1] L. L. Thurstone, "A Law of Comparative Judgment." *Psychological Review,* 1927 (a), (34), 273-86. L. L. Thurstone, "Psychophysical Analysis." *American Journal of Psychology,* 1927 (b), (38), 368-89. W. P. Tanner and J. A. Swets, "The Human Use of Information: I. Signal Detection for the Case of the Signal Known Exactly." *Transcripts of IRE Professional Group on Information Theory,* 1954, PGIT-4, pp. 213-21. D. M. Green and J. A. Swets, *Signal Detection Theory and Psychophysics.* New York: Wiley, 1966. J. P. Egan, "Recognition Memory and the Operating Characteristic." Indiana University, Hearing and Communication Lab, AFCRC-TN-58-51, AD 152650, 1958. W. A. Wickelgren and D. A. Norman, "Strength Models and Serial Position in Short-Term Recognition Memory." *Journal of Mathematical Psychology,* 1966 (3), 316-47.

[2] Thurstone, "A Law of Comparative Judgment" and "Psychophysical Analysis." W. A. Wickelgren, "Unidimensional Strength Theory and Component Analysis of Noise in Absolute and Comparative Judgments." *Journal of Mathematical Psychology,* 1968 (5), 102-22.

The probability of correct choice on a multiple-choice recognition task decreases the greater the similarity of the incorrect alternatives to the correct alternatives. For example, if one has learned the paired associate *ball-pink*, the probability of correct recognition is lower when the choice is between *pink, red, blue,* and *maroon* than when the choice is between *pink, sad, ant,* and *democracy,* because in the former case one must remember the exact response, whereas in the latter case one need only remember that it was a color. Most of you know that the difficulty of a multiple-choice test depends greatly on the nature of the incorrect alternatives (the distractors). Whenever you can rule out an absurd alternative answer, your probability of guessing correctly will be greater than chance, even if you have little specific knowledge. In strength-theoretic terms, the difficult distractors are those that have a greater strength of association to the cues in the question. The greater the average strength of the distractors, the smaller the difference in strength (d') between the distractors and the correct alternative.

The dependence of multiple-choice recognition memory on the similarity of the incorrect alternatives to the target alternative has some important implications for the police line-up, the procedure by which eyewitnesses identify criminal suspects. If the criminal is known to be a young red-haired male, it is obviously no protection whatsoever to a young red-haired male suspect to see if an eyewitness can pick him out of a line-up composed of blonds, dark-haired men, women, and an aged derelict. I feel sure that this extreme is not typical of police line-ups, but the similarity of the distractor subjects to the suspect depends on thousands of variables, and the greater the similarity of the distractors to the suspect, the more protection the suspect receives. Where do we draw the line? It is an important legal question, and it needs a precise answer if we are to provide more nearly equal (if not perfect) justice for all individuals.

Small Recall: The Maximum Rule

When one is testing recall with the alternative responses selected from a small population (such as the set of binary digits "0" and "1"), there may be little difference between what is nominally called a recall test and what is nominally referred to as a multiple-choice recognition test, provided the subject is highly familiar with the response set. However, when there were only four possible alternatives, one study found substantially shorter latencies in paired-associate recall than in four-alternative multiple-choice recognition for the same pairs.[3] Thus, while it may be reasonable to apply the maximum decision rule to recall from a small population of alternatives, even in this case recall may be a fundamentally different mechanism from recognition. One possibility is that multiple-choice recognition is *sequential* retrieval of familiarity for each alternative followed by choice of the alternative with the maximum strength. On the other hand, recall may be a *simultaneous* comparison of alternative strengths: parallel retrieval of all the associations with the stimulus item followed by choice of the alternative with the maximum strength.

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[3] D. A. Norman and W. A. Wickelgren, "Strength Theory of Decision Rules and Latency in Retrieval from Short-Term Memory." *Journal of Experimental Psychology,* 1969 (6), 192-208.

Large Recall: The High-Threshold Rule

When the number of response alternatives is extremely large, as in a continuous word-word paired-associate recall task of hundreds or thousands of different words, the subject's ability to recall a response word given a stimulus word probably depends virtually entirely on a specific association between the stimulus word and the response word. Response sets are largely eliminated as a factor. Under such conditions it is not reasonable to assume the maximum decision rule, since the number of alternatives is not well defined. When the number of response alternatives is extremely large, it seems more reasonable to assume a *high-threshold rule* as suggested by Bahrick, wherein the subject responds only if the strength of association between the stimulus and a response exceeds some high threshold.[4] If the recall threshold is very high, an incorrect alternative will have little or no chance of exceeding the threshold, and errors will consist largely of omissions, as appears often to be the case in such situations. Intrusions (incorrect guesses) may result either because an incorrect item occasionally exceeds threshold strength or, more likely, because the subject resorts to random guessing when no alternative exceeds the threshold.

RETRIEVAL: DIRECT ACCESS OR SEARCH?

There are two hypotheses regarding memory retrieval: direct access and search. The direct-access hypothesis has often been linked closely to the continuous strength hypothesis of memory representation, and the search hypothesis has often been linked to a finite-state, even an all-or-none, trace-representation hypothesis. It is also possible to combine a direct-access retrieval hypothesis with an all-or-none trace hypothesis and to combine a search-retrieval hypothesis with a continuous strength hypothesis.

One can also assume various mixtures of direct access and search. For example, many memory researchers have accepted Kintsch's hypothesis that recognition is a direct access process, while recall is a search process. Juola, Atkinson, and their colleagues proposed that recognition has two

[4] H. P. Bahrick, "The Ebb of Retention." *Psychological Review,* 1965 (72), 60-73. W. A. Wickelgren, "Strength/Resistance Theory of the Dynamics of Memory Storage," in D. H. Krantz, R. C. Atkinson, R. D. Luce, and P. Suppes (eds.), *Contemporary Developments in Mathematical Psychology,* San Francisco: Freeman, 1974.

stages. First, there is a rapid direct-access process that retrieves a strength for the test item (or pair). If strength is above some high criterion, a "yes" response is made. If it is below some low criterion, a "no" response is made. If it is between the two criteria, the subject invokes a slower sequential search process to attempt to find the test item on the appropriate list in memory.[5]

It does not seem necessary to consider these more complex hypotheses, since the existing evidence is consistent with a simple direct-access theory of retrieval for both recall and recognition at both short and long retention intervals. In the present section we will carefully describe the direct-access and search hypotheses regarding recognition and recall and then examine the evidence for recognition and recall at both short and long retention intervals.

The Direct-Access Theory

When a test item or pair of items is presented in a recognition test, the strength of the relevant associations either between the pair of items or between the item and the context (list cues) is assumed to be directly retrieved. Although the retrieval of trace strength is assumed to be a direct-access process without need for a search or scanning of alternative locations or traces in memory, the retrieval of trace strength is still assumed to require time. Thus, the retrieval of strength grows over a period of time following presentation of the test item(s). Data collected by Reed indicate a period on the order of a second or two for relatively complete retrieval of trace strength in recognition memory.[6] At any time during the retrieval process subjects can make a decision regarding the test item(s) based on the strength retrieved thus far by comparing that strength to some criterion and deciding "yes" if the strength lies above the criterion and "no" otherwise.

The simplest direct-access hypothesis for recognition memory is that the retrieval process for one association is unaffected by the strength of any other associations in memory. In particular, if one is retrieving the strength of an *AB* test association, the strengths of *AC* or *DB* associations are assumed to be irrelevant to the retrieval process for the *AB* association. There is some evidence supporting this hypothesis with respect to the ultimate asymptotic retrieved strength of the *AB* association (after two seconds or more of retrieval time),[7] though the rate of retrieving an *AB* association appears to be slowed slightly by the presence of a strong *AC* association. Existing data on retrieval dynamics are consistent with the direct-access theory in which the rate of retrieving an *AB* association is somewhat slower in the presence of an *AC* interfering association.[8]

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[5] W. Kintsch, *Learning, Memory, and Conceptual Processes.* New York: Wiley, 1970. J. F. Juola and R. C. Atkinson, "Memory Scanning for Words vs. Categories." *Journal of Verbal Learning and Verbal Behavior,* 1971 (10), 522-27. J. F. Juola, I. Fisher, C. T. Wood, and R. C. Atkinson, "Recognition Time for Information Stored in Long-Term Memory." *Perception and Psychophysics,* 1971 (10), 8-14.

[6] A. V. Reed, "Speed-Accuracy Trade-Off in Recognition Memory." *Science,* 1973 (181), 574-76.

Any theory of recall must almost necessarily assume the possibility of competition between *AB* and *AC* associations under some conditions. In the usual recall procedure a choice is required among all the possible responses to the *A* stimulus. Thus, a comparison of the relative strengths of associations between *A* and all possible responses is logically required in the recall task, although if omissions are permitted, the competition may only be among those associations that exceed the recall threshold. In recall as well as in recognition there is evidence that the presence of a strong *AC* association retards the rate of retrieval of strength for an *AB* association, and that the magnitude of this associative interference effect on retrieval appears to be exactly the same in recall as in recognition.[9] This suggests that the same retrieval process is used in both recall and recognition. We shall argue that this retrieval process is very likely direct access in both recall and recognition.

The Search Theory

Even when the direct-access process logically involves the retrieval of more than one associative strength, as in recall, this retrieval is assumed to proceed in parallel, that is, simultaneously for all associations. By contrast, a search theory assumes that memory retrieval for even a single association requires sequential (serial) accessing of several different memory traces (whether varying continuously in strength or being all or none). Sternberg, for example, assumes that a subject recognizing whether an item came from some previously presented list sequentially searches every memory location used to store items from the previous list, looking for a match between the test item and an item in memory.

Sternberg distinguishes two types of search: self-terminating and exhaustive. The self-terminating search is assumed to end whenever a match is made between the test item and an item in memory, while the exhaustive search compares the test item with *every* item stored in some set of memory locations, whether a match occurs part way through the set or not. The self-terminating search appears a priori to be more functional, but Sternberg felt that certain evidence compelled the assumption that recognition memory search (scanning) was exhaustive rather than self-terminating.[10]

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[7] W. A. Wickelgren, "Exponential Decay and Independence from Irrelevant Associations in Short-Term Recognition Memory for Serial Order." *Journal of Experimental Psychology,* 1967 (73), 165-171. L. Postman, K. Stark, and J. Fraser, "Temporal Changes in Interference." *Journal of Verbal Learning and Verbal Behavior,* 1968 (7), 672-94.

[8] W. A. Wickelgren and A. T. Corbett, "Associative Interference and Retrieval Dynamics in Yes-No Recall and Recognition." *Journal of Experimental Psychology: Human Learning and Memory,* 1977.

[9] Wickelgren and Corbett, "Associative Interference." J. P. Houston, "Competition in the Two-Factor Theory of Forgetting." *Journal of Verbal Learning and Verbal Behavior,* 1968 (7), 496-500.

Even the most extreme search theories have always explicitly or implicitly assumed that the subject need not search all the millions of locations or associations in memory, but can instead directly access a relatively small population of alternatives (small set) through which the sequential search takes place. Clearly it would be more parsimonious if a direct-access theory could be made to fit all the facts of memory retrieval, since a large component of retrieval is assumed to be by direct access under both the search and direct-access hypotheses.

Let's consider two recall tasks in order to illustrate the assumptions of the typical search theory. In tests by probe recall of verbal short-term memory for a list of digits, the subject is instructed to produce the item that followed the probe digit in the preceding list. For this task Sternberg assumed the following retrieval process: (1) The subject has direct access to the memory locations corresponding to the successive list items. (2) The subject begins to search sequentially through the list (typically from the beginning) until a match is achieved to the probe item. (3) The item in the next memory location is retrieved and produced as a response. Note that Sternberg assumed that the search process in recall was self-terminating. It is of course logically possible that recall involves a self-terminating search while recognition involves an exhaustive search, but such an assumption is less elegant than assuming the same type of search for each.

Another type of recall task involves presentation of a category such as *animals* and a letter such as *H*. Subjects are instructed to recall a member of the category whose name starts with the particular letter, in this case an animal whose name begins with *H*. A typical search theory of such recall assumes that the subject first directly accesses all storage locations corresponding to members of the category and begins to search sequentially for one whose name begins with *H*.[11] Here the recall search process is usually assumed to be self-terminating.

Recognition Memory

Short-term retention. In a 1966 study of enormous influence, Sternberg presented a list of anywhere from one to six digits followed by a probe digit that might or might not be in the list. He then measured the reaction time subjects took to decide whether the probe digit was a member of the previously memorized list (target set). The time to make this decision appeared to increase linearly with the length of the target list, that is, the reaction-time function was a straight line. Furthermore, the same rate of increase obtained both for probe items in the list (old items) and for probe items not in the list (new items). Finally, Sternberg found no significant differences in the reaction time for old items chosen from different serial positions within lists of any given length. These results led Sternberg to conclude that recognition memory involved an exhaustive serial search of the target list. If the search proceeded from the beginning of the list and was self-terminating, one might expect a primacy effect: faster reaction times for probe items from the initial positions in the list. Alternatively, one might expect a recency effect if they began scanning from the end of the list. Furthermore, if the search were self-terminating, the old items would, on the average, be encountered after searching only half of the items in the target set, while saying "no" to new items would require searching the entire set. This leads to the prediction that the rate of increase in the reaction time as a function of set size for old items would be a half the rate for new items, contrary to what was obtained.[12] The predicted functions for both exhaustive and self-terminating search are shown in Figure 15-3.

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[10] S. Sternberg, "High-Speed Scanning in Human Memory." *Science,* 1966 (153), 652-54. S. Sternberg, "Memory Scanning: Mental Processes Revealed by Reaction Time Experiments." *American Scientist,* 1969 (57), 421-57.

[11] J. L. Freedman and E. F. Loftus, "Retrieval of Words from Long-Term Memory." *Journal of Verbal Learning and Verbal Behavior,* 1971 (10), 107-15.

Since under other conditions one typically obtains primacy and recency

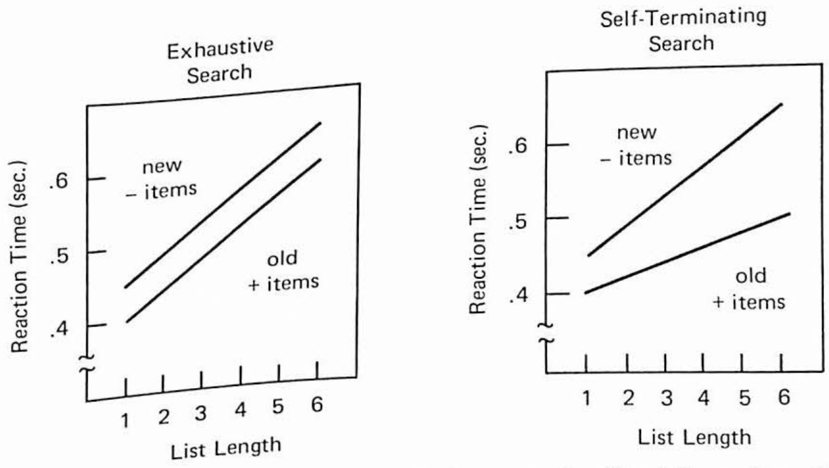

Figure 15-3. Example predictions of the reaction time to say "yes" to old items (items that were in the target list) and "no" to new items (items that were not in the target list), according to a serial exhaustive search theory and a serial self-terminating search theory. Sternberg's experimental findings were in accord with the exhaustive search theory, where the rate of increase in reaction time as a function of list length is the same for old and new items. If the search were self-terminating, the rate for old items should be half the rate for new items.

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[12] Sternberg, "High-Speed Scanning."

effects in the strengths of items in lists (measured by the probabilities of correct recognition), it might appear that a direct-access strength theory should predict primacy and recency effects in decision latencies for recognition memory as well. Furthermore, while a direct-access strength theory should predict that the reaction times would increase with longer lists, owing to their lower average strength in memory, it is not simple to make a direct-access strength theory predict a linear increase in reaction time with increasing target set size. Accordingly, Sternberg's results were taken as strong evidence for an exhaustive search process in recognition retrieval from short-term verbal memory.

Sternberg's findings have been replicated so long as there was strict adherence to critical aspects of his procedure, but these findings are not generally true using other experimental procedures, the results of which strongly favor the direct-access theory over the search theory. Furthermore, the conditions required to obtain Sternberg's results suggest a very plausible explanation in terms of direct-access strength theory of why Sternberg obtained no primacy or recency effects.

To obtain Sternberg's results, the presentation rate must be relatively slow (on the order of one item per second or slower), and there must be a relatively long (two second) interval between the end of the list and the presentation of the probe item. These conditions allow ample opportunity for rehearsal, which could easily eliminate any differences in degree of learning that typically account for primacy effects and any differences in retention interval that result in recency effects. Strong primacy and recency effects *are* obtained when presentation rates are faster and testing is immediate, precisely as expected by direct-access strength theory.[13]

If the linear increase in recognition latency with increasing set size were established as a valid indicator of retrieval time in recognition memory, it would still be a strong point in favor of the search hypothesis. However, the linear increase has been established only for relatively small variations in set sizes (from one to six in Sternberg's study). It is a fact that any steadily increasing function will be reasonably well fit by a linear function over a small range of variation in the independent or dependent variable. The range of variation in the independent (set size) variable and the dependent (reaction time) variable in these recognition reaction time studies has been very small; therefore, it is not surprising that they are well fit by linear functions.

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[13] R. E. Morin, D. V. DeRosa, and V. Stultz, "Recognition Memory and Reaction Time." *Acta Psychologica,* 1967 (27), 298-305. R. E. Morin, D. V. DeRosa, and R. Ulm, "Short-Term Recognition Memory for Spatially Isolated Items." *Psychonomic Science,* 1967 (9), 617-18. M. C. Corballis, "Serial Order in Recognition and Recall." *Journal of Experimental Psychology,* 1967 (74), 99-105. K. Kirsner and F. I. M. Craik, "Naming and Decision Processes in Short-Term Recognition Memory." *Journal of Experimental Psychology,* 1971 (88), 149-57. D. Burrows and R. Okada, "Serial Position Effect in High-Speed Memory Search." *Perception and Psychophysics,* 1971 (10), 305-8. M. C. Corballis, J. Kirby, and A. Miller, "Access to Elements of a Memorized List." *Journal of Experimental Psychology,* 1972 (94), 185-190.

In addition, the significance of the supposedly linear increase in reaction time is seriously compromised, under even these limited conditions, by the complete failure to deal with an important confounding factor, namely, speed-accuracy tradeoff. Subjects can trade off speed for accuracy in any known reaction time task, including recognition memory retrieval.[14] Thus, there appears to be some sort of time or accuracy criterion that subjects are capable of varying. This produces corresponding variation in the actual reaction times and associated error rates in any given condition. In every study that I have seen in which error rates have been reported, error rates have increased substantially with increasing list length in the Sternberg paradigm.[15] Such results suggest that the recognition times for long list lengths are underestimated, perhaps seriously. The form of the speed-accuracy trade-off is such that at the very high levels of accuracy that subjects are typically instructed to obtain, small differences in error rate translate into extremely large differences in reaction time. Thus, the actual reaction times obtained in these studies at varying error rates for different set sizes may not be very meaningful.

Finally, even under the standard Sternberg conditions, Baddeley and Ecob have found that presenting a digit more than once in a target list reduces the reaction time for that digit by comparison to nonrepeated digits in the same list and by comparison to comparable lists without repeated items. Such results are precisely what is expected by direct-access strength theory and appear to be inconsistent with an exhaustive search theory. Baddeley and Ecob obtained a linear increase in reaction time with increasing list length and an absence of serial position effects, precisely as obtained by Sternberg.[16] This demonstrates that the findings claimed to support an exhaustive theory can be obtained under conditions where another finding clearly contradicts it.

Long-term retention. As we have pointed out, it was never very reasonable to assume that a serial search process operated as a general model of long-term recognition. One must assume, at a minimum, that subjects can directly access some relevant subset of memory locations to search, as it would simply require too much time to search all contents of long-term memory, even at the "high-speed" scanning rates proposed by Sternberg.

One of the most promising paradigms for evaluating a search theory of long-term recognition memory is the category-exemplar recognition task: deciding whether a word is a member of some category (bird, city, female

[14] Reed, "Speed-Accuracy Trade-Off" W. A. Wickelgren, "Speed-Accuracy Trade-Off and Information-Processing Dynamics." *Acta Psychologica,* 1976.

[15] W. A. Wickelgren, "Dynamics of Retrieval," in Deutsch and Deutsch, *Short-Term Memory,* pp. 233-55.

[16] A. D. Baddeley and J. R. Ecob, "Reaction Time and Short-Term Memory: Implications of Repetition Effects for the High-Speed Exhaustive Scan Hypothesis." *Quarterly Journal of Experimental Psychology,* 1973 (25), 229-40.

name, etc.). Some support for the search theory was obtained in studies that found recognition memory reaction time increased with the number of examples in a category, but there have been a couple of failures to obtain this finding, and such category-membership recognition decisions appear likely to be mediated by the strength of the association between an example and a category concept.[17] There is at present no evidence requiring one to reject the more parsimonious direct-access retrieval hypothesis in favor of a more complex explanation of direct access of the category set followed by search of the locations in the category set.

Recall

Short-term retention. In the probe-digit experiment performed by Sternberg, recall times increased monotonically and approximately linearly with serial position, with fastest times for the first position and the slowest times for the last item in the list.[18] However, it clearly could not be assumed that all subjects were beginning their search at the beginning of the list, since the time to recall the second item, given the first, increased as a function of list length. There were some more complex discrepancies as well. To resolve these discrepancies, Sternberg proposed that subjects sometimes begin their search at other positions in the list. However, it is equally plausible to assume that under Sternberg's conditions, which encouraged rehearsal, the strength of associations decreased systematically with increasing serial position. Since recall time should decrease with increasing associative strength, Sternberg's results are easily accounted for by a direct-access strength theory. Once again the significance of the linear increase in recall time with either list length or serial position is very questionable considering the likely possibility of speed-accuracy trade-off. Furthermore, even the monotonic increase in recall reaction times as a function of serial position (pure primacy effect) is very rarely observed in either short-term or long-term recall studies. For example, under conditions that miniize rehearsal of prior items, Norman found a simple recency effect, wherein the fastest probe reaction times were for the last items in the list, and other investigators have found both primacy and recency effects in probe-recall studies.[19]

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[17] T. K. Landauer and J. L. Freedman, "Information Retrieval from Long-Term Memory: Category Size Affect Categorization Time?" *Journal of Verbal Learning and Verbal Behavior*, 1970 291-95. D. E. Meyer, "On the Representation and Retrieval of Stored Semantic Information." *Cognitive Psychology*, 1970 (1), 242-300. J. F. Juola and R. C. Atkinson, "Memory Scanning for Words vs. Categories." *Journal of Verbal Learning and Verbal Behavior*, 1971 (10), 522-27. A. J. Wilkens, "Conjoint Frequency, Category Size, and Categorization Time." *Journal of Verbal Learning and Verbal Behavior*, 1971 (10), 382-85. A. M. Collins and M. R. Quillian, "Does Category Size Affect Categorization Time?" *Journal of Verbal Learning and Verbal Behavior*, 1970 (9), 432-38. H. Egeth, N. Marcus, and W. Bevan, "Target-Set and Response-Set Interaction: Implications for Models of Human Information Processing." *Science*, 1972 (176), 1447-1448.

[18] S. Sternberg, "Retrieval of Contextual Information from Memory." *Psychonomic Science*, 1967 (8), 55-56.

Long-term retention. As in the case of recognition time, greater frequency of presentation of a pair of items decreases the probe-recall latency of the response to the stimulus for a very large number of trials beyond the last error in paired associate-learning.[20] In long-term recall of a category member beginning with some letter of the alphabet, Freedman and Loftus have shown that the number of examples in a category has no necessary effect on reaction times when the category cues are strongly associated to the response items, as for example in recalling an animal whose name starts with the letter *Z* to which a correct response is *Zebra*.[21] Thus, it is the strength of association between the cues and the response that appears to be the variable that significantly influences recall reaction time rather than the number of items in the relevant categories.

RECOGNITION AND RECALL COMPARED

Is Recognition Better than Recall?

In most instances recognition scores are higher than recall scores. One reason for this, as Davis, Sutherland, and Judd emphasized, is that the number of alternatives is typically much higher in a recall test than in a recognition test, and this leads to differences that are the result of chance guessing alone. When such differences are eliminated, by having the number of alternatives on the recognition test equal the number on the recall test or when the chance effects of guessing are eliminated by a correction procedure, some or all of the difference between recognition and recall scores is eliminated.[22]

The greatest problem in most previous comparisons of recall and recog-

[19] D. A. Norman, "Acquisition and Retention in Short-Term Memory." *Journal of Experimental Psychology,* 1966 (72), 369-81. N. C. Waugh, "Retrieval Time in Short-Term Memory." *British Journal of Psychology,* 1970 (61), 1-12. D. V. De Rosa and R. Baumgarte, "Probe-Digit Recall of Items from Temporally Organized Memory Sets." *Journal of Experimental Psychology,* 1971 (91), 154-58.

[20] See the long list of studies in Wickelgren, "Dynamics of Retrieval."

[21] Freedman and Loftus, "Retrieval of Words."

[22] R. Davis, N. S. Sutherland, and B. R. Judd, "Information Content in Recognition and Recall." *Journal of Experimental Psychology,* 1961 (61), 422-29. Norman and Wickelgren, "Strength Theory of Decision Rules." D. M. Green and F. L. Moses, "On the Equivalence of Two Recognition Measures of Short-Term Memory." *Psychological Bulletin,* 1966 (66), 228-34. W. Kintsch, "Recognition and Free Recall of Organized Lists." *Journal of Experimental Psychology,* 1968 (78), 481-87.

nition scores has been the tendency for egregious confounding of the difference in the retrieval process (recall versus recognition) with differences in the memories being tested. For example, there have been numerous comparisons of recognition of words from some previously presented list with free recall of the words on the list. Under many such circumstances recognition may be nearly perfect while free recall produces less than half of the words on the list. The comparison has little meaning: Recognition tests tap associations in both directions, from the words to the context (or list-name concepts) and from the context to the words. Free recall depends primarily on associations from the context to the words. Since direct associations in this direction are typically very weak, free recall often uses a much more complex process of subjective organization of the list, in which subjects recall words in clusters using associations between related words in the list or between superordinate category labels (such as vehicle) that are associated with various words in the list (for example, car, truck, bus).[23] Because the associations that mediate free-recall performance are almost completely different from the ones that mediate item recognition for words in the same list, any differences between recognition and free recall are more plausibly attributed to differences in the associations tapped by the two retrieval processes than to differences in the retrieval processes themselves. Such an interpretation is consistent with the fact that using lists with a high level of inter-item associative strength or organization into categories facilitates free recall far more than it facilitates item recognition.[24]

In reaction to some of these inconclusive comparisons of recognition and free recall, the incomparable Endel Tulving, who likes to poke holes in other people's theories, performed an "inappropriate" recall and recognition experiment in which recall performance was actually superior to recognition. Watkins used the same idea to produce spectacularly higher performance in recall than in recognition. He gave subjects paired associates of the form SPANI-EL, AMNES-IC, and EXPLO-RE. In the recall condition subjects were given the initial five letters and asked to produce the last two letters. In the recognition test they were given only the last two letters mixed with distractor letter pairs and asked to identify which pairs had occurred in the preceding list. Subjects clearly recognized that the two parts of the items on the original paired-associate list combined to form English words and had no idea they were later going to be tested for recognition of the last two letters in isolation. After a retention interval of a little over half an hour, performance on the recognition test (for the last two letters) was only slightly above chance, while on the recall test it was extremely high.[25] Once again completely different associations were being tapped by the recognition and recall tests, which totally confounds the tests as comparisons of the recognition and recall retrieval processes.

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[23] J. J. Jenkins and W. A. Russell, "Associative Clustering During Recall." *Journal of Abnormal and Social Psychology,* 1952 (47), 818-21. J. Deese, "From the Isolated Verbal Unit to Connected Discourse," in C. N. Cofer (ed.), *Verbal Learning and Verbal Behavior.* New York: McGraw-Hill, 1961, pp. 11-31. E. Z. Rothkopf and E. U. Coke, "The Prediction of Free Recall from Word-Association Measures." *Journal of Experimental Psychology,* 1961 (62), 433-38. W. A. Bousfield, "The Occurrence of Clustering in the Recall of Randomly Arranged Associates." *Journal of General Psychology,* 1953 (49), 229-40. B. H. Cohen, "Some-or-None Characteristics of Coding Behavior." *Journal of Verbal Learning and Verbal Behavior,* 1966 (5), 182-87. E. Tulving and Z. Pearlstone, "Availability vs. Accessibility of Information in Memory for Words." *Journal of Verbal Learning and Verbal Behavior,* 1966 (5), 381-91. G. Mandler, "Organization and Memory," in K. W. Spence and J. T. Spence (eds.), *The Psychology of Learning and Motivation: Advances in Research and Theory,* Vol. 1. New York: Academic Press, 1967, pp. 328-72.

[24] C. N. Cofer, "Does Conceptual Organization Influence the Amount Retained in Immediate Free Recall?" in B. J. Kleinmuntz (ed.), *Concepts and the Structure of Memory.* New York: Wiley, 1967, pp. 181-214. W. Kintsch, "Recognition and Free Recall of Organized Lists." *Journal of Experimental Psychology,* 1968 (78), 481-87.

A Theoretical Comparison of Recall and Recognition

There are three primary issues in a theoretical comparison of recall and recognition: (1) Is the same memory store used in both recall and recognition? (2) Is the same retrieval process used in both recall and recognition? (3) Is the same decision process used in recall and recognition? Whenever the answer to one of these questions is that there is a difference, then one wants to know the nature of the difference.

Storage. It is widely believed that recall and recognition tap the same basic memory storage system, and there is no reason to doubt this assumption. It would be dysfunctional for humans to store the same information in two different storage systems since the same information is relevant to answering either type of question.

However, the belief that the same memory system is tapped by both recall and recognition does not imply that any comparison of recall and recognition tests retrieval of exactly the same associations. As was discussed at length in the previous section, most comparisons of recall and recognition have probably confounded the comparison of output processes by tapping very different memory traces in recall and recognition.

In recognition and free recall of items, Tulving has pointed out that recall and recognition can be considered end points on a continuum defined by the number of *retrieval cues* (and therefore the number of memory traces) used in the retention test. Tulving and Watkins performed an experiment which, as they admit, demonstrated the obvious: that recall of the words in a list increases as you provide the subject with an increasing number of letters from the words to be recalled.[26] Recognition represents the most extreme form of such a test in which one provides all of the letters in a word. There is certainly a great deal of merit in considering the retrieval cues operative in any retention test. This is simply another way of discussing the associations that are tapped by any retention test.

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[25] E. Tulving, "When Is Recall Higher than Recognition?" *Psychonomic Science,* 1968, (10), 53-54. M. J. Watkins, "When is Recall Spectacularly Higher than Recognition?" *Journal of Experimental Psychology,* 1974 (102), 161-63.

An ideal comparison of output processes in recall and recognition probably occurs for *AB* paired associates. Even here two recall tests, forward recall from *A* and backward recall from *B*, may be necessary in order to tap the same memory traces as are tapped by a single *AB* pair recognition test.[27]

Retrieval. As we discussed previously, the existing evidence supports a direct-access retrieval hypothesis for both recall and recognition. Furthermore, it appears that the rate of retrieval in *AB* paired-associate recognition memory is precisely the same as in forward recall of *B* given *A* as a cue. (The retrieval rate for backward recall has not yet been determined.)[28] Hence, there is reason to believe that the same basic retrieval process may be employed in recall and recognition.

Decision. In the decision stage, conventional recall and yes-no recognition memory necessarily differ, because recall is a comparative judgment of many possible *B* responses, while yes-no recognition is an absolute judgment with respect to a single *B* response. Both the motor responses and the logical character of the decision are different.

Multiple-choice recognition can provide essentially the same decision problem as small recall (recall from a small population of alternatives). However, as discussed previously, multiple-choice recognition may not be a single elementary retrieval task, but rather one in which a succession of recognition retrievals are performed followed by choice of the alternative with the greatest retrieved strength.

Finally, a yes-no decision task has been invented for recall of paired associates. One presents the *A* item, to which the subject is to recall the *B* item. After a variable lag, either the correct *B* item or an incorrect *D* item is presented, and the subject must respond "yes" or "no" within 0.4 sec. Since it has been established that 0.4 sec is too little time to perform above chance on a test of *AB* paired-associate recognition memory, we know that the high level of performance achieved by subjects in this task was the result of recalling *B* to the *A* cue.[29]

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[26] E. Tulving and M. J. Watkins, "Continuity Between Recall and Recognition." *American Journal of Psychology*, 1973 (86), 739-48.

[27] Wickelgren and Corbett, "Associative Interference." G. Wolford, "Function of Distinct Associations for Paired-Associate Performance." *Psychological Review*, 1971 (78), 303-13.

[28] *Ibid.*

[29] *Ibid.*

Overview. The retrieval process appears to be identical, and the same memory system is used in both memory output tasks. The two principal differences between recall and recognition are that (1) typically (although not necessarily) there are important differences in the decision stage, and (2) typically there are differences in the associations tapped by recall and recognition, because recognition has more retrieval cues than recall.

STATE-DEPENDENT RETRIEVAL

Fugue and Multiple Personality

In a state of fugue amnesia an individual loses personal memory for his or her identity and life experiences but retains the ability to understand, speak, read, and write language as well as semantic knowledge of the world that is unrelated to individual identity.[30] There is no evidence that the laws of memory are different for episodic and semantic memory, but the existence of patients who show a selective loss for episodic memory (if this were rigorously established) suggests that there is an anatomical or physiological differentiation between the two types of memory that might be associated with functional psychological differences. However we know too little yet to say whether this is so and what those differences if any, might be.

In fugue amnesia an individual may begin to establish a new personal identity and is able to remember personal experiences acquired during the fugue state. When the individual "awakens" from the fugue state and regains his or her original identity, the episodic memories acquired during the fugue state may be unretrievable. In rare circumstances an individual may periodically alternate between two or more different personalities, with a set of episodic memories for each personality and an inability to remember the episodic memories associated with the personality not now "in control."

The dissociation of episodic memories is not necessarily absolute in either fugue or multiple personality. Individuals are sometimes able to remember events that occurred during the fugue state when they return to their previous identities, and there are various patterns of access to episodic memories in different cases of multiple personality. For example, it may be that one of the personalities can remember only its own set of episodic memories, but another personality can remember its own set and the set appropriate to other personality.

In terms of the acquisition, storage, and retrieval distinction, fugue is a retrieval deficit. New memories are acquired in the fugue state, and old memories are still stored, since they can often be recovered. Fugue and multiple personality are cases of state-dependent retrieval in which the accessibility of memories for retrieval is dependent on the state of the individual. Dreams, hypnotic trance, and drug states may provide other examples of such state-dependent retrieval.

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[30] For fascinating discussions of fugue, multiple personality, and other memory disorders see I. M. L. Hunter. *Memory*. Maryland: Penguin, 1964. See also Th. Ribot, *Diseases of Memory: An Essay in the Positive Psychology*. Englewood Cliffs, N. J.: Prentice-Hall, 1896.

Dreams and Hypnosis

It is sometimes suggested that the loss of memory in fugue or multiple personality is similar to that which occurs to normal people who can't remember much of what occurred during dream states once they wake up: An analogous phenomenon occurs when hypnotizable subjects are given posthypnotic suggestions not to remember what happened during hypnosis when they return to the normal waking state. To the extent that such inaccessible memories can be restored by a return to the dream or hypnotic states, the deficit during the waking state is one of retrieval, not of storage or acquisition. No one knows whether memories acquired in previous dreams are more retrievable in another dream state than while awake. Anecdotally, recovery from posthypnotic amnesia requires specific hypnotic suggestion, not just reinstatement of the state of hypnotic trance.

Drugs

There is some evidence for *state-dependent recall* under alcoholic intoxication, but the same dependency does not hold when the material is tested by recognition memory.[31] Thus, an *AB* paired associate learned in a state of alcoholic intoxication might be recalled better when a subject is again intoxicated and given the *A* stimulus than when he or she recalls while sober, but the same does not hold when subjects are asked to recognize whether an item or pair was presented. For recognition it appears to make no difference whether the state has changed or stayed the same. However, the issue is somewhat complicated by the fact that initial learning is typically poorer in a state of alcoholic intoxication than in a sober state. The extreme condition of *alcoholic blackout* appears to be primarily a matter of reduced acquisition during the blackout stage rather than a matter of state-dependent retrieval. There is no evidence that memories learned during one blackout become available again during another blackout. Although alcoholic intoxication appears to have some state-dependent retrieval properties, it has never been determined whether these are selective for personal episodic memories or whether they affect episodic and semantic memory equally. We are far from having an adequate experimental basis for drawing conclusions about even the distinct existence of fugue, multiple personality, and state-dependent retrieval under drugs, sleep, hypnosis, etc., let alone their mechanisms.

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[31] D. A. Overton, "A State-Dependent Learning Produced by Alcohol and Its Relevance to Alcoholism," in B. Kissen and H. Begleiter (eds.), *The Biology of Alcoholism, Vol. 2: Physiology and Behavior.* New York: Plenum Press, 1972, pp. 193-217. D. W. Goodwin, B. Powell, D. Bremer, H. Hoine, and J. Stern, "Alcohol and Recall: State-Dependent Effects in Man. *Science,* 1969 (163), 1358-60.

RETRIEVAL FACTORS

In Chapter 1 we distinguished between learning and memory on the one hand and performance on the other. Performance on a retrieval task is used to measure the strength of memory traces, but there are a number of factors at the time of retrieval that can affect memory performance besides trace strength. Recall is generally more susceptible to retention failure than recognition memory as a result of adverse retrieval factors, but under proper conditions recognition can be affected by every retrieval factor that affects recall. Nevertheless, these retrieval factors can be minimized by experimental controls so that retention tests can provide a relatively pure measure of the strength of memory traces in storage.

Competition

Competition between *AB* and *AC* associations is an associative interference factor that operates at the time of retrieval to reduce recall, but not usually recognition, performance. To the extent that subjects are uncertain about which of two (or more) associations to a stimulus to recall, performance will obviously be reduced. A recognition test of *AB* usually avoids competition by not requiring a choice between *AB* and *AC*. A recall test that permits more than one response also avoids competition. The original cause of competition is the establishment during the retention interval of competing *AC* associations to an originally learned *AB* association. However, the interference operates at the time of retrieval.

Retrieval Time

Limiting the time for recognition or recall is another retrieval factor that depresses memory performance. Retrieval time affects both recall and recognition, but because recognition and recall performance approach limits at retrieval times on the order of two or three seconds, it is easily possible to eliminate this factor by allowing sufficient time for recognition or recall.[32] An illustration of the time course of memory retrieval is shown in Figure 15-4.

[32] Reed, "Speed-Accuracy Trade-Off in Recognition Memory."

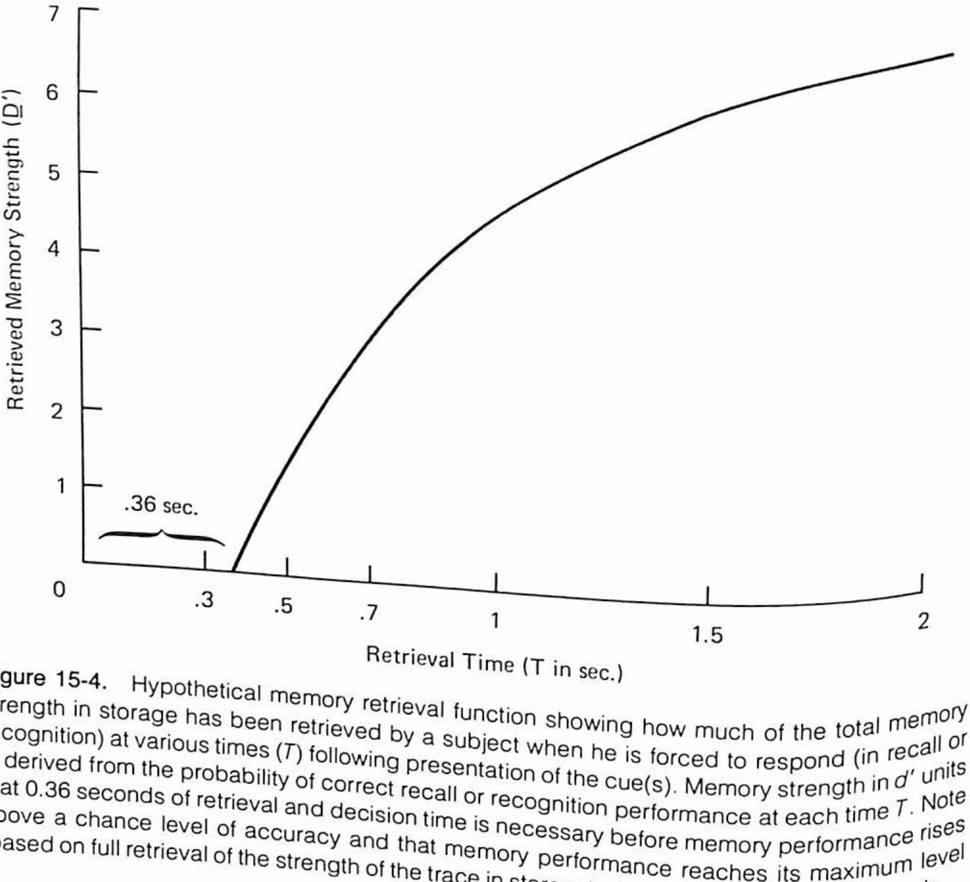

Figure 15-4. Hypothetical memory retrieval function showing how much of the total memory strength in storage has been retrieved by a subject when he is forced to respond (in recall or recognition) at various times (*T*) following presentation of the cue(s). Memory strength in *d'* units is derived from the probability of correct recall or recognition performance at each time *T*. Note that 0.36 seconds of retrieval and decision time is necessary before memory performance rises above a chance level of accuracy and that memory performance reaches its maximum level (based on full retrieval of the strength of the trace in storage) after about two or three seconds.

Arousal

At a gross level we know that a subject's state of arousal can have a substantial effect on performance, in that a subject who is asleep will not respond at all on a memory test. Several studies on level of arousal in waking subjects have failed to demonstrate much of an effect. In a study by Uehling and Sprinkle, increasing arousal by exposure to noise facilitated recall, but the effects were very small. Experiments attempting to increase arousal by other means have sometimes failed to find any significant effect.[33] Presumably the arousal level of subjects in experiments is generally very high, such that further increases in arousal level may not have any significant effect on memory retrieval. Conditions that increase arousal in drowsy subjects (such as might be produced by loss of sleep) could conceivably have a much more potent effect on memory retrieval.

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[33] B. S. Uehling and R. Sprinkle, "Recall of a Serial List as a Function of Arousal and Retention Interval." *Journal of Experimental Psychology*, 1968 (78), 103-6. R. G. Green, "Effects of Being Observed on Short- and Long-Term Recall." *Journal of Experimental Psychology*, 1973 (100), 395-98.

Fatigue and Satiation

Surprisingly, I know of no studies of the effect of general fatigue on memory retrieval, but it is a reasonable possibility. Some important distinctions to make in understanding fatigue effects include distinguishing (1) physical from mental fatigue, (2) different types of mental fatigue, (3) fatigue from low arousal, and (4) fatigue from associative proactive interference factors.

One specific extreme of the fatigue hypothesis concerns whether it is possible to (temporarily) overuse an association so that it is "tired out." So far as I know repeated *AB* recall does not eventually produce an inability to recall *B* when given *A*, but there have been demonstrations of the so-called *semantic satiation* effect—that the dominance of word meanings or associations can be altered by repeated presentation or production of a word.[34] You can produce the effect for yourself by repeating a word over and over again rapidly. After a time the word may begin to sound strange, and the meaning of the word, as indexed by the associations you produce to it, will often be altered.

Motivation and Repression

We pointed out in Chapter 1 that motivation and attention are two of the primary factors that affect performance. Control of motivation is a considerable problem in studies of animal learning and memory, but it is typically assumed that human subjects are usually optimally motivated by instructions and the desire to do well or please the experimenter. In cases where motivation has been deliberately manipulated in studies of human memory retrieval by such means as varying monetary incentives or punishing incorrect responses with electric shock, the incentive condition at the time of recall has typically had little or no effect, which confirms the assumption that motivation is typically not a significant retrieval factor in human memory experiments.[35]

According to Freud and other psychoanalysts, some emotionally disturbed persons (subconsciously) block recall of unpleasant memories, even when forced to attend to cues that would be completely sufficient to produce recall in normal persons. This phenomenon, called *repression*, is similar in some respects to fugue or multiple personality though much less global in scope. Rather than losing all personal episodic memory, a disturbed patient may repress only some particularly painful memories concerning traumatic events. The circumstances surrounding a death in the family or some other traumatic event may appear to be completely forgotten by such an individual and resist ordinary attempts by others to revive these memories. The memory is assumed to be in storage and can indeed be elicited under special conditions, such as free associations, dreams, or hypnosis. However, under normal conditions recall of repressed memories is blocked because of its direct or indirect association to some unpleasant emotion. The scientific status of repression is uncertain.

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[34] W. E. Lambert and L. A. Jakobovits, "Verbal Satiation and Changes in Intensity of Meaning." *Journal of Experimental Psychology*, 1960 (60), 376-83. S. Fillenbaum, "Verbal Satiation and Changes in Meaning of Related Items." *Journal of Verbal Learning and Verbal Behavior*, 1963 (2), 263-71. R. Dolinsky and G. M. Barbarosh, "Changes in the Dominance of Word Associations Following Verbal Repetition." *Journal of Verbal Learning and Verbal Behavior*, 1967 (6), 327-31.

[35] B. A. Heinrich, "Motivation and Long-Term Memory." *Psychonomic Science*, 1968, (12), 149-50. D. D. Wickens and C. K. Simpson, "Trace Cue Position, Motivation, and Short-Term Memory." *Journal of Experimental Psychology*, 1968 (76), 282-85. G. R. Loftus and T. D. Wickens, "Effect of Incentive on Storage and Retrieval Processes." *Journal of Experimental Psychology*, 1970 (85), 141-47.

Attention and Distraction

If a subject pays no attention to the relevant stimulus material, there is little possibility of correct performance on a recall or recognition test. Attention is probably not an all-or-none process, but a process with various degrees of attentional set. In human memory experiments, attention to the relevant cues is instructionally controlled to the point where it is typically not considered to be a factor. However, as discussed in Chapters 3 and 4, the process by which animals come to attend to the relevant cues plays an important role in many animal discrimination-learning experiments.

Ordinarily recall is useful, but, there are times when recall of unpleasant events serves no useful purpose, and it would be better to keep from thinking about such things. Storage loss can be very slow, especially for events that were extremely arousing at the time of learning. To prevent recall of unpleasant memories, people use the method of *distraction:* avoiding the cues associated with unpleasant events or selectively not attending to them. For example, a popular meditation practice typically involves the repetition of a single word (mantra)—almost any word will do—to prevent recall of potentially disturbing thoughts. The method of falling asleep by counting sheep while imaging them jumping over a fence keeps both verbal and imaginal memory occupied and thereby helps to prevent recall of problems or events of the day that might otherwise keep one awake.

Distraction is not repression, because when attention is focused on the relevant cues, the unpleasant memories are recalled. However, because of the associative character of memory, an unpleasant event will be recalled only if one of the cues associated with its representation is present in consciousness.

Altered Relevant Cues (Stimulus Change)

If consonant trigrams (ZBK, RGM, and so on) are used as stimuli in a paired-associate learning task, and a subsequent retention test presents only the second letter of each trigram as a cue, recall and recognition performance will be depressed compared to a condition in which the entire consonant trigram is presented. Deleting a relevant cue depresses performance because subjects have attended somewhat to the deleted cues during learning and therefore have a stronger total association with all the attributes of the compound stimulus than with any one attribute. There are situations in which cue selection on the part of subjects is so strong that one dominant stimulus attribute is as effective as the entire compound. However, any variation in the cue selection process or any encoding of a compound stimulus as a single chunk will produce the result that no single attribute is so effective as the entire compound in producing recall or recognition.[36]

The addition of relevant cues can also adversely affect memory retrieval. If the consonant trigram in the previous example were presented as a hidden figure embedded in a complex visual display, it could be very difficult for a subject to detect the relevant portion of the stimulus to recognize or use as a cue for recall.

Recently there has been a series of studies initiated by Light and Carter-Sobell and Tulving and Thomson on the effects of altering parts of compound stimuli from acquisition to retrieval. For example, if *raspberry jam* is presented during learning, there will be poorer recognition memory of the noun *jam* if *jam* occurs at the time of the retention test, in conjunction with an adjective that elicits a different meaning of the word, such as *traffic jam*. In these studies subjects were explicitly instructed that the biasing adjective at the time of the retention test was irrelevant, but they had considered the biasing adjective to be relevant at the time of acquisition.[37] Thus, such studies primarily exemplify the effects of deletion of a relevant cue from acquisition to retrieval. However, to the extent that subjects are influenced by the biasing adjective (which they clearly are, despite the instructions) these studies also involve the addition of relevant cues at the time of retrieval.

You demonstrate recall failure owing to inadequate retrieval cues whenever you fail to recall almost all the countless millions of facts you have learned. "Ah," you may say, "but that is because I did not *want* to think of these facts, and anyhow I was thinking about something else and can only have one thought at a time." But what does it mean to want to think about a particular thing, and how do you manage (when you do) to keep your thoughts on that subject and not on countless other thoughts stored in your memory? You accomplish this, at least in part, because memory is associative, and the next thought you have is one that is strongly associated to what you were just thinking about. Your current set of thoughts are very likely the retrieval cues for your next set of thoughts. We do not know how big such "thought sets" are, and we do not know how goals direct our thinking, but the associative character of memory plays a large role in the selectivity of our stream of thought.

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[36] For a review of work on compound stimulus change see J. Richardson, "Cue Effectiveness and Abstraction in Paired-Associate Learning." *Psychological Bulletin,* 1971 (75), 73-91.

[37] L. L. Light and L. Carter-Sobell, "Effects of Changed Semantic Context on Recognition Memory." *Journal of Verbal Learning and Verbal Behavior,* 1970 (9), 1-11. E. Tulving and D. M. Thomson, "Retrieval Processes in Recognition Memory: Effects of Associative Context." *Journal of Experimental Psychology,* 1971 (81), 116-24.

Understanding the associative character of human memory and the importance of retrieval cues can help you to be less forgetful in everyday life. How often have you said to yourself, "I must remember to bring (or do) *X* (something) when I leave tomorrow morning (or this afternoon, tonight, etc.) for school (or work or home, etc.)," and then forgotten to bring (or do) *X* when the time came? You can reduce this forgetfulness substantially by remembering that memory is associative and considering the specific retrieval cues that will be available to you at the time you wish to recall something. Do not just think, "I must remember *X*." Instead think something like, "When I go out that door, I want to remember *X*." This associates the retrieval cue *door* to *X*. If you have the time, you can put a tag (tape, glove, whatever) on the doorknob to serve as a more distinctive retrieval cue (same principle as a string on your finger). Of course if you want to be certain to bring something, putting the thing itself in front of the door is the best retrieval cue of all! Whatever you do, do not expect an associative memory to produce a particular output without an appropriate input. You only get thoughts out of your memory if you put thoughts into it, in more ways than one!

Altered Irrelevant Cues (Context Change)

When each stimulus of a ten-item paired-associate list is printed with ink of a different color, color can be a relevant stimulus attribute that subjects frequently use to determine the correct response in addition to, or even in preference to, the verbal attributes of the stimulus. When color is deleted or changed in a retention test, one is studying the effects of altering relevant cues in compound stimuli. However if at the time of learning all the stimulus items are presented in the same color, color is an irrelevant (context) cue. Other context cues that are always present in any learning experiment include the characteristics of the experimental room, background auditory stimulation, the characteristics of the person running the experiment, the way the subject is sitting, the apparatus being used, and so on.

Over the years many memory researchers have confused the effects of altering relevant elements of compound stimuli with the effects of altering irrelevant contextual stimuli. For example, the studies of recognition memory for nouns with biasing adjectives that were thought to be concerned with the effects of altering context were actually concerned with altering relevant attributes of compound stimuli. McGeoch and Irion's classic book on human learning also attempted to make a strong case for changes in background context as a retrieval factor depressing recall, but careful study of the experiments they cited reveals that when studies that changed relevant cues are eliminated from consideration, negative effects of irrelevant context changes have generally not been observed.[38]

By contrast, changes in background context from a first to a second list, such as moving the subject from one room to another, do appear to reduce proactive and retroactive interference between the two lists.[39] Since changing the context between the two lists makes context cues relevant, such effects of contextual change on associative interference are completely consistent with the general hypothesis that context cues that are nominally irrelevant are, in general, functionally irrelevant to learning and memory performance. Irrelevant contextual attributes are generally not encoded as part of a memory trace.

The effect of context on reducing associative interference raises the more general point that cues that are irrelevant for some purposes may be relevant for other purposes. Whenever a subject learns two lists, especially those that involve some of the same stimulus items, it may be very important for the subject to differentiate between the lists in some way in memory. Such list differentiation can be achieved merely by the use of a time or order cue, such as first list or second list. Any additional contextual change from the first to the second list might aid in this differentiation, but existing evidence indicates that the encoding of such list differentiation cues is done by means of very abstract concepts that may have very little to do with the specific physical stimuli in the background context. For example, Strand found as great a reduction of retroactive interference when subjects were removed from a room between the learning of lists and brought back to the same room as when they were brought to a different room.[40]

Viewed in a broader functional context, it would be extremely dysfunctional for memory retrieval to be substantially influenced by altering irrelevant context cues. For example, in learning to forage for edible plants and avoid poisonous plants, it would have deleterious effects for survival if human beings had not possessed a very effective mechanism for distinguishing between the relevant characteristics of plants and such irrelevant characteristics as background context. (Of course human judgment of what is relevant is far from perfect, but the mechanism for determining relevancy is there, and attributes judged to be irrelevant at the time of learning are not encoded in memory. Alteration of such irrelevant cues from acquisition to retention appears to have no effect on memory performance.)

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[38] McGeoch and Irion, *The Psychology of Human Learning*, pp. 448-51.

[39] K. Dallett and S. G. Wilcox, "Contextual Stimuli and Proactive Inhibition." *Journal of Experimental Psychology*, 1968 (3), 475-80. B. Z. Strand, "Change of Context and Retroactive Inhibition." *Journal of Verbal Learning and Verbal Behavior*, 1970 (9), 202-6.

[40] *Ibid.*

Encoding Variability

Since experimentally produced changes in relevant cues from acquisition to retrieval produce poorer performance, it seems reasonable to assume that this process may go on spontaneously, even with no change in the nominal stimulus, as a result of changes in stimulus encoding on the part of the subject. The hypothesis that encoding variability contributes to forgetting has been around for some time, but its theoretical potential for explaining a wide variety of learning and memory phenomena was realized in a precise way only after Estes developed the stimulus sampling theory in 1950.[41] A few memory theorists go so far as to use encoding variability as a complete substitute for the assumption of any loss of memory in storage. It is sometimes alleged that retrieval interference factors can account for all forgetting, which eliminates any need to assume trace decay or storage interference processes.

In a rather illogical way, the results of studies by Wilder Penfield of brain stimulation in conscious patients undergoing neurosurgery are sometimes cited in this context. Penfield discovered that electrical stimulation of certain parts of the brain produced surprisingly detailed recall of incidents, purportedly from the person's earlier life, that had not been consciously thought of in years.[42] Some people jumped to the conclusion that such evidence supported the proposition that nothing was ever forgotten in human memory but only became increasingly difficult to retrieve. Unfortunately, since there was no systematic investigation of the memories produced by these subjects, it is not possible to distinguish their productions from those characteristic of dreams and fantasies. Even if it were possible to demonstrate that the incidents had happened, it is completely gratuitous to generalize from this to the proposition that all the memories that were ever acquired are still stored somewhere in the brain. We know that under ordinary conditions we do not recall most of the things we have learned, but this is often because we are not given the proper cues. It is illogical to conclude from the fact that we sometimes recall things we have not recalled in a long time, whether because of brain stimulation or the presentation of some relevant cue, that nothing is ever forgotten. It is not contradictory to this hypothesis, but it does not provide any significant support for it either.

As Postman and Underwood have pointed out, direct studies of the encoding variability hypothesis have demonstrated little or no variability in the encoding of the same nominal stimulus under the conditions of standard verbal learning experiments.[43] Thus, the forgetting observed in these situations cannot be accounted for solely by means of this retrieval interference factor.

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[41] W. K. Estes, "Toward a Statistical Theory of Learning," *Psychological Review*, 1950 (57), 94-107. E. Martin, "Stimulus Meaningfulness and Paired-Associate Transfer: An Encoding Variability Hypothesis." *Psychological Review*, 1968 (75), 421-41. G. H. Bower, "Stimulus-Sampling Theory of Encoding Variability," in A. W. Melton and E. Martin (eds.), *Coding Processes in Human Memory*. Washington, D. C.: V. H. Winston and Sons, 1972, pp. 85-123.

[42] W. Penfield, "The Interpretive Cortex." *Science*, 1959 (129), 1719-25.

It is obvious that encoding variability can occur, and that when it does occur it can be a substantial source of retrieval interference. It is very likely a significant factor in the recall of childhood memories. Since children are so rapidly expanding the set of concepts with which they encode events in the world, events that are coded equivalently by adults may be encoded in different ways by children, especially if they occur at different times in the child's development. Thus, even though encoding variability may often be controlled experimentally so as to be a negligible factor in certain human learning and memory experiments, it is almost certainly an important retrieval factor under other conditions.

Inference (Reconstruction)

As we saw in Chapter 10, most of the questions we can answer on the basis of stored information are not answered on the basis of a single, previously stored association. Rather, we combine separately stored associations by means of inference processes to answer a rich variety of possible questions. Furthermore, our perception of events makes use of our associative memory to draw inferences at the time of perception concerning "what must have happened." By and large such inference is desirable. However, when completely veridical testimony is required, as from a witness in a court of law, such inferential use of human memory (whether at the time of original perception of an event or at the time of retrieval) can be a substantial source of interference.

Bartlett's classic studies of the recall of stories established that subjects make substantial use of inference from their general semantic memory in reconstructing stories.[44] Human beings are forever reconstructing "what must have happened" by means of inferences from fragmentary perception and memory. Furthermore, the inference process in retrieval is so automatic that most of the time we are completely unaware of what we directly recall and what we infer, except when our attention is specifically drawn to the distinction, as under cross examination in a law court.

The use of inference in recall extends even to presuppositions contained in the questions we ask. Loftus and Palmer conducted experiments in which subjects viewed films of automobile accidents and then answered questions about events in the film. The question "About how fast were the cars going when they smashed into each other?" produced higher speed estimates than questions using the verbs *bumped, collided, contacted,* or *hit,* instead of *smashed*. A week later subjects who heard the verb *smashed* were more likely to answer the question "Did you see any broken glass" affirmatively, even though there was no broken glass in the film.[45] Such results point out how extraordinarily difficult it is to secure accurate testimony without unwarranted inferences.

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[43] L. Postman and B. J. Underwood, "Critical Issues in Interference Theory." *Memory and Cognition*, 1973 (1), 19-40.

[44] F. C. Bartlett, *Remembering: A Study in Experimental and Social Psychology*. Cambridge: Cambridge University Press, 1932.

SUMMARY

1. Elementary recognition memory is based on the feeling of familiarity aroused by some material. Elementary recall is the generation of a new thought in response to one's prior thoughts. Experiments attempt to control prior thoughts by stimulus cues.
2. Complex retrieval tasks are composed of a sequence of elementary recognitions and recalls.
3. Perceptual recognition is the activation of the node representing a stimulus. Recognition memory is the feeling of familiarity generated by this process. The two processes are probably closely linked, and perhaps inseparable under normal conditions.
4. Item memory is almost certainly a form of associative memory based either on (1) the strength of association between the item node and one or more context nodes, or (2) the associations of the attributes (constituents) of the item to each other or to the chunk node for the item.
5. There are two stages in output from memory: (1) retrieval (of associations), and (2) decision (based on the strength(s) of the association(s) retrieved).
6. Yes-no recognition memory probably uses a criterion-decision rule of responding "yes" only if the strength (familiarity) of the retrieved association exceeds some criterion. Multiple-choice recognition and small recall (recall from a small set of alternatives) probably use the maximum decision rule of choosing the alternative with maximum associative strength. Large recall very likely follows a high-threshold decision rule whereby the correct alternative is recalled only if it exceeds some high threshold strength of association to the retrieval cues.

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[45] E. F. Loftus and J. C. Palmer, "Reconstruction of Automobile Destruction: An Example of the Interaction Between Language and Memory." *Journal of Verbal Learning and Verbal Behavior,* 1974 (13), 585-89.

7. Retrieval is by a direct-access process for both recognition and recall. No search of memory is required in elementary retrieval tasks. Memory search is a complex retrieval process involving a sequence of elementary recalls and recognitions, as in trying to remember someone's name by giving oneself a succession of cues.
8. Recognition and recall appear to use the same (associative) memory system, the same retrieval process, and sometimes even the same decision rules, though typically they use different ones. Generally, there are more retrieval cues—and therefore more associations being tapped—in recognition than in recall.
9. Fugue, multiple personality, dreams, hypnotic trance, and some drug states may produce a condition in which some memories are unlikely to be retrieved, even though they may be readily retrievable under other conditions. Such state-dependency of retrieval is not well understood.
10. Some of the factors that can affect both recognition and recall performance at the time of retrieval are: (1) retrieval time, (2) motivation, (3) attention, (4) addition or deletion of cues that are treated as relevant by the subject, (5) encoding variability, and (6) inferences by the subject. Even competition can affect a recognition test, though usually it is only a factor in recall.
11. Most of these retrieval factors probably affect recall more than recognition, but there does not appear to be any qualitative difference in the retrieval factors that affect recall and recognition.
12. The effect of the following factors on elementary retrieval appears to be minimal: (1) retrieval time beyond a few seconds, (2) arousal (provided the subject is awake), (3) general fatigue, (4) differences between moderately high and high levels of motivation, and (5) context changes in irrelevant cues.
13. It is likely (but not definitely established) that all retrieval factors can be experimentally controlled so as to provide relatively pure measures of the strengths of memory traces in storage. Recognition tests are probably somewhat easier to control in this regard.

Recommended Reading

I wish to draw your attention to the following books, which I feel are particularly good treatments of topics related to learning and memory. Most of them are cited often in the text.

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